Global Infrastructure Investor Association
Promoting Private Investment in Infrastructure

ARUP

Catalysing hydrogen investment

What the market needs to deliver investment in hydrogen infrastructure

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About Arup

Arup is a global independent firm of more than 15,000 designers, planners, engineers, architects, consultants and technical specialists, working across every aspect of today's built environment. The company was founded on the belief that the built environment has a central role in creating a safer, more sustainable planet. Together we help our clients solve their most complex challenges – turning exciting ideas into tangible reality as we strive to find a better way and shape a better world.

About Global Infrastructure Investor Association (GIIA)

The Global Infrastructure Investor Association is a membership body representing the leading investors and advisers in global infrastructure. GIIA works closely with policy makers, regulators and other industry bodies to achieve our shared ambition of increasing infrastructure investment around the world. We aim to do this by building understanding of the positive role played by private investors in long-term infrastructure and helping to shape the policies that will facilitate further investment to meet the low carbon, digital and transport infrastructure requirements of the future.

Acknowledgements

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Foreword

Governments, regulators, investors, and operators around the world are grappling with the complex challenge of how to meet society's growing future energy needs whilst decarbonising the global economy.

The Global Infrastructure Investor Association (GIIA), representing more than 80 of the leading private investors and advisors in global infrastructure, was formed in 2016 in order to engage on exactly this kind of fundamental policy conundrum. Drawing on the expertise of our membership - led by Arup and supplemented by expert investor insight - this report, Catalysing Hydrogen Investment, provides a comprehensive and thought-provoking analysis of the issues to be addressed and, crucially, some clear and targeted recommendations for policy makers to consider.

GIIA members currently own and manage nearly $1tn of infrastructure assets on six continents, $4bn of which is in hydrogen infrastructure. The last 12 months have seen further impressive growth in renewables with a 39% increase in investment worth $90bn which directly resulted in a global increase of GW capacity by 35% to 130GW. We estimate that at any given point in time there is at least $200bn of new capital ready to invest in infrastructure. This is a positive indicator of investor appetite to kickstart a global effort to reach our climate goals.

Across key markets and economies, we are seeing major policy and spending announcements, but while the context may differ there is a golden thread that consistently appears – by combining government funds with private capital we can achieve much, much more, and faster.

As we look ahead to COP26 its safe to say that there is not a moment to lose to get the right frameworks in place to drive the future investment needed to deliver the infrastructure we all require.

Lawrence Slade
CEO, GIIA

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Introduction

The future of hydrogen – told through the uncompromising eyes of potential investors.

Hydrogen is a hot topic and there is no shortage of reports on the subject.

Written by Arup in collaboration with the GIIA, this report is centred on the opinions of investors from around the world, gathered through a survey of GIIA members and in-depth interviews.

It therefore presents the sentiments of the world's leading fund managers, insurance investors, pension funds and a sovereign wealth fund. Their opinions matter because these are the decision makers that hold the purse strings when it comes to private sector investment in hydrogen infrastructure.

Many of the facts about hydrogen are well-known to many readers and these are presented in this report, drawing on Arup's research and experience as a global infrastructure advisory firm.

However, the novelty of this report is that it looks at hydrogen through the uncompromising eyes of investors, with analysis of feedback which identifies barriers to investment in the infrastructure required to enable the hydrogen economy.

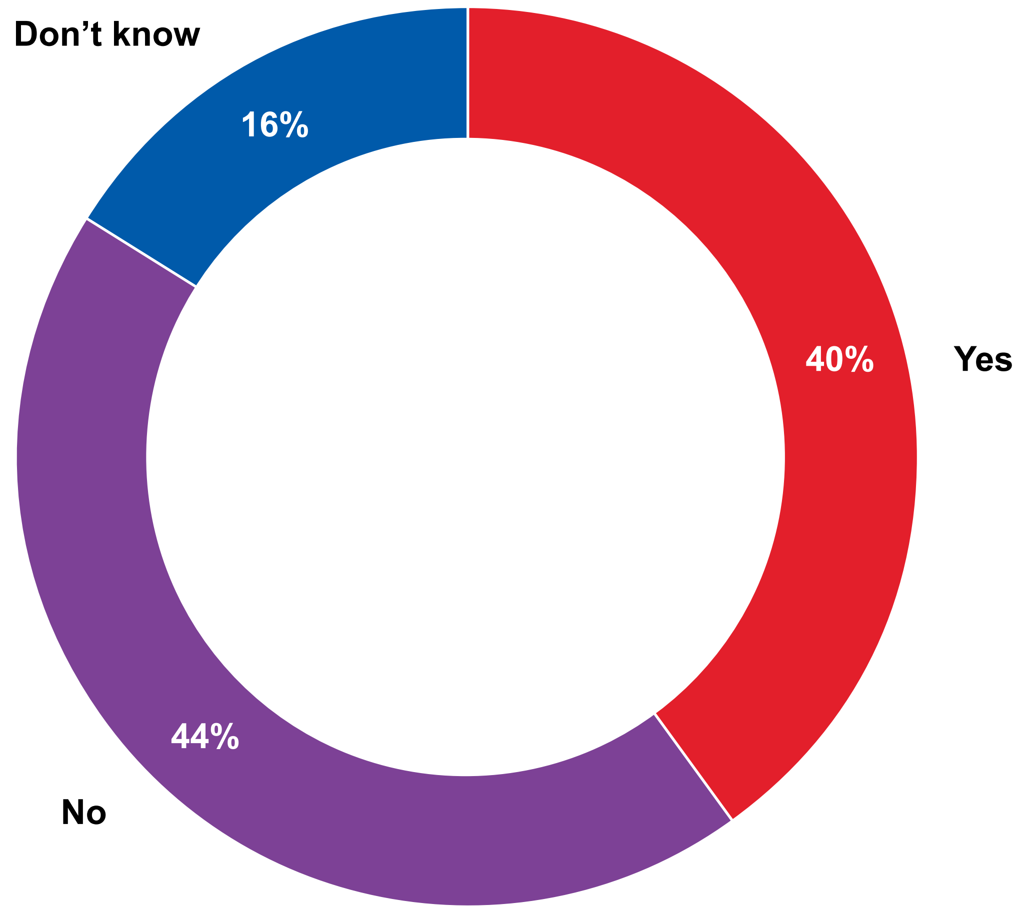
Perhaps most importantly, it also proposes interventions that policymakers and regulators could take to overcome the barriers currently faced.

The sentiments of investors are at the heart of this study, with results from the survey presented at the beginning of each section to serve as a launch pad for Arup's analysis. But we want it to be more than an interesting read; it is a call to action for policy makers to create the right environment to catalyse private sector investment and kickstart the hydrogen economy.

Hydrogen can play a significant role in decarbonising the global economy, but it needs to be done cleanly

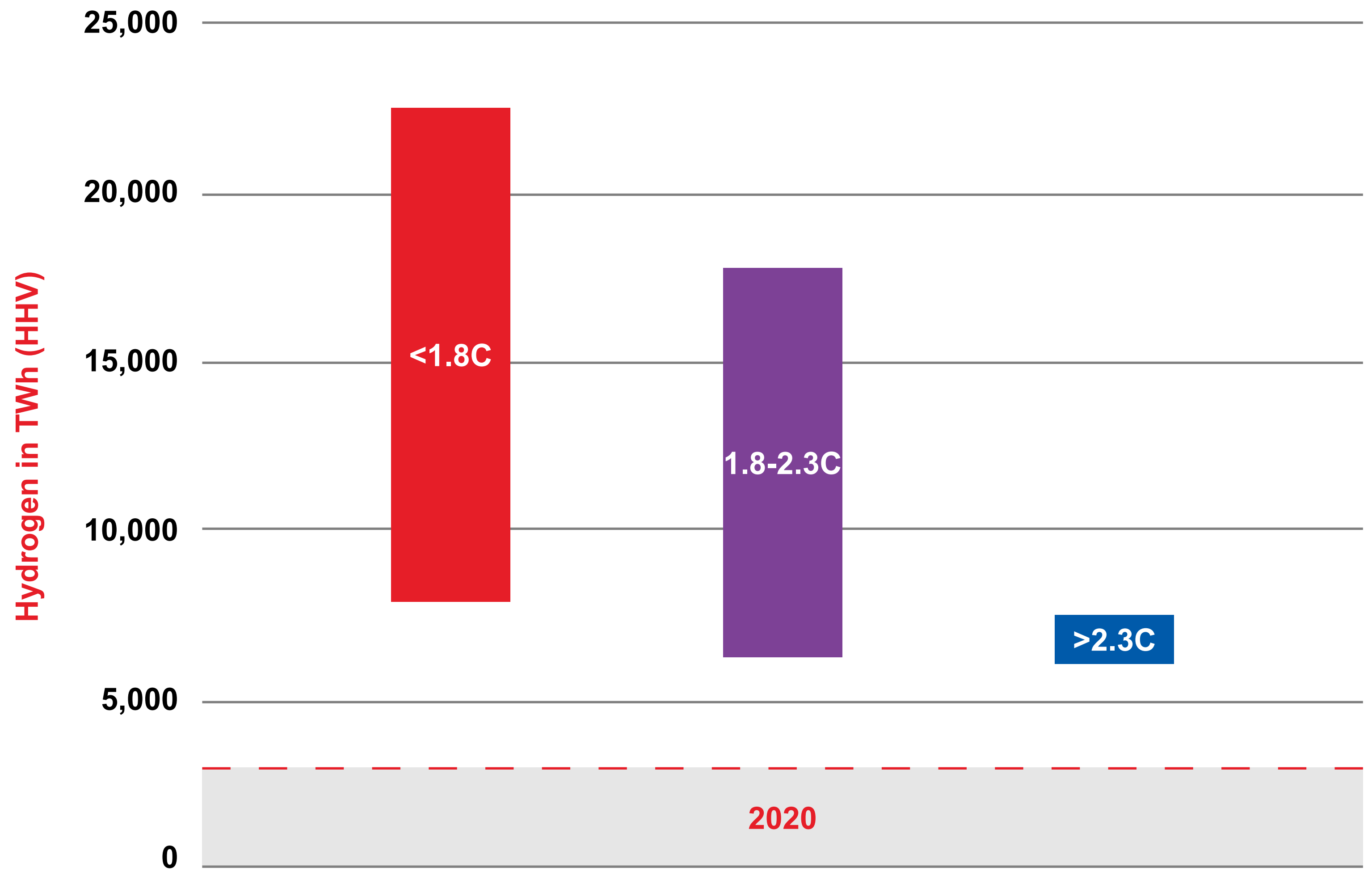
The historic Paris Agreement in 2015 attracted signatories from 195 countries across the globe. This demonstration of international unity in combatting climate change requires further strengthening, more ambitious targets and associated policy action to reduce emissions.

Do you believe energy infrastructure investment trends are aligned with the Paris Agreement?



This sentiment is echoed in a report by the International Panel for Climate Change where the need for "immediate, rapid and large-scale cuts to greenhouse gas (GHG) emissions" was highlighted as being paramount to keep climate goals on track and limit global warming to well below 2°C above pre-industrial levels, and to pursue efforts to limit the temperature increase to 1.5°C.

A report from the World Energy Council showed that global hydrogen demand is expected to grow significantly under a range of decarbonisation scenarios, from about 3,000 TWh in 2020 to between 6,000 to 23,000 TWh by 2050, depending on the assumptions. This range is predicted to be equivalent to about 6% to 25% of global energy demand in 2050.



Ranges of forecast hydrogen demand by 2050 for three global warming scenarios (from World Energy Council's review of various forecasts).

Currently most hydrogen production is carbon-intensive but it doesn't need to be

The term "hydrogen economy" was coined in 1970 and captures the vision of using hydrogen as a low carbon energy vector because it does not contain carbon and only produces water when used.

Currently, about 98% of the hydrogen produced today is derived from carbon-intensive processes, so a new approach to manufacturing is required if it is to be credible as a low carbon energy source.

Although at present hydrogen is largely used in oil refining and chemical production, there is great potential for it to be used as a fuel in other sectors to reduce GHG emissions, provided it is made in a way that minimises the amount of carbon dioxide and methane that is emitted in the process.

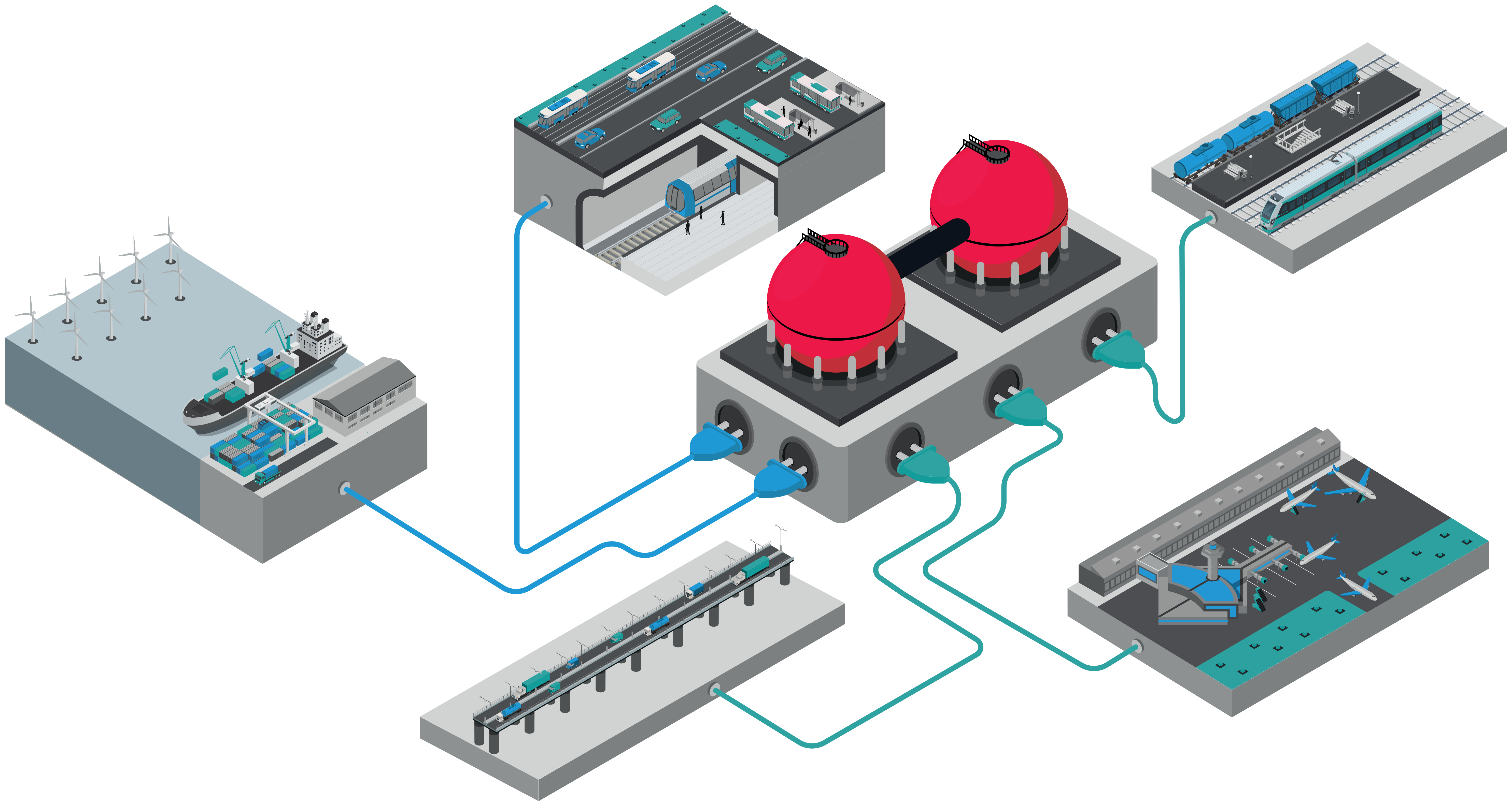
$530m
electrolyser plants

$2.8bn
liquefaction plants

$430m
hydrogen storage assets

$70.5bn
gas storage and distribution assets

GIIA members have interests in electrolyser plants to the value of more than $530m, liquefaction plants of $2.8bn and hydrogen storage assets worth $430m. In addition, GIIA members have stakes in gas storage and distribution assets totalling $70.5bn, refineries worth $9.2bn and gas generation plants to the value of $10.5bn. These assets, currently dependent on carbon-intensive commodities, could consider hydrogen in their future to help navigate the energy transition pathway.



Huge investment in infrastructure required

The Hydrogen Council estimates that total investment in the hydrogen value chain will exceed a cumulative $300 billion by 2030 and, according to the Energy Transitions Commission, reach approximately $15 trillion by the 2050.

$300bn
by 2030

$15tn
by 2050

This demonstrates the substantial need and opportunity for investment within the hydrogen value chain, with large-scale hydrogen infrastructure investment viewed as a key enabler to allow low carbon hydrogen to decarbonise industry and the wider economy.

However, there are currently barriers holding back private sector investment in hydrogen infrastructure and this report will explain what is needed to overcome these barriers.

The question is no longer why hydrogen? – but how, when and how much?

Hydrogen has experienced cycles of enthusiasm and subsequent disappointment for several decades.

However, the current positive sentiment is underpinned by a shift from the previous principles-based approach to development of coherent pathways to deployment, accompanied by predictions for investment scale and mechanisms for securing financial returns.

The risks of climate change are at the forefront of public consciousness, even as reports of extreme weather events around the world have become commonplace. This increased awareness has translated into political pressure for action and resulted in a wave of hydrogen focussed strategies, plans and policies around the world.

In addition, the positive lessons learned from the deployment of renewable technologies since the start of the millennium have served to build confidence in the policy and regulatory support mechanisms that can drive investment and kick-start a virtuous cycle of cost reduction and increased investment in hydrogen.

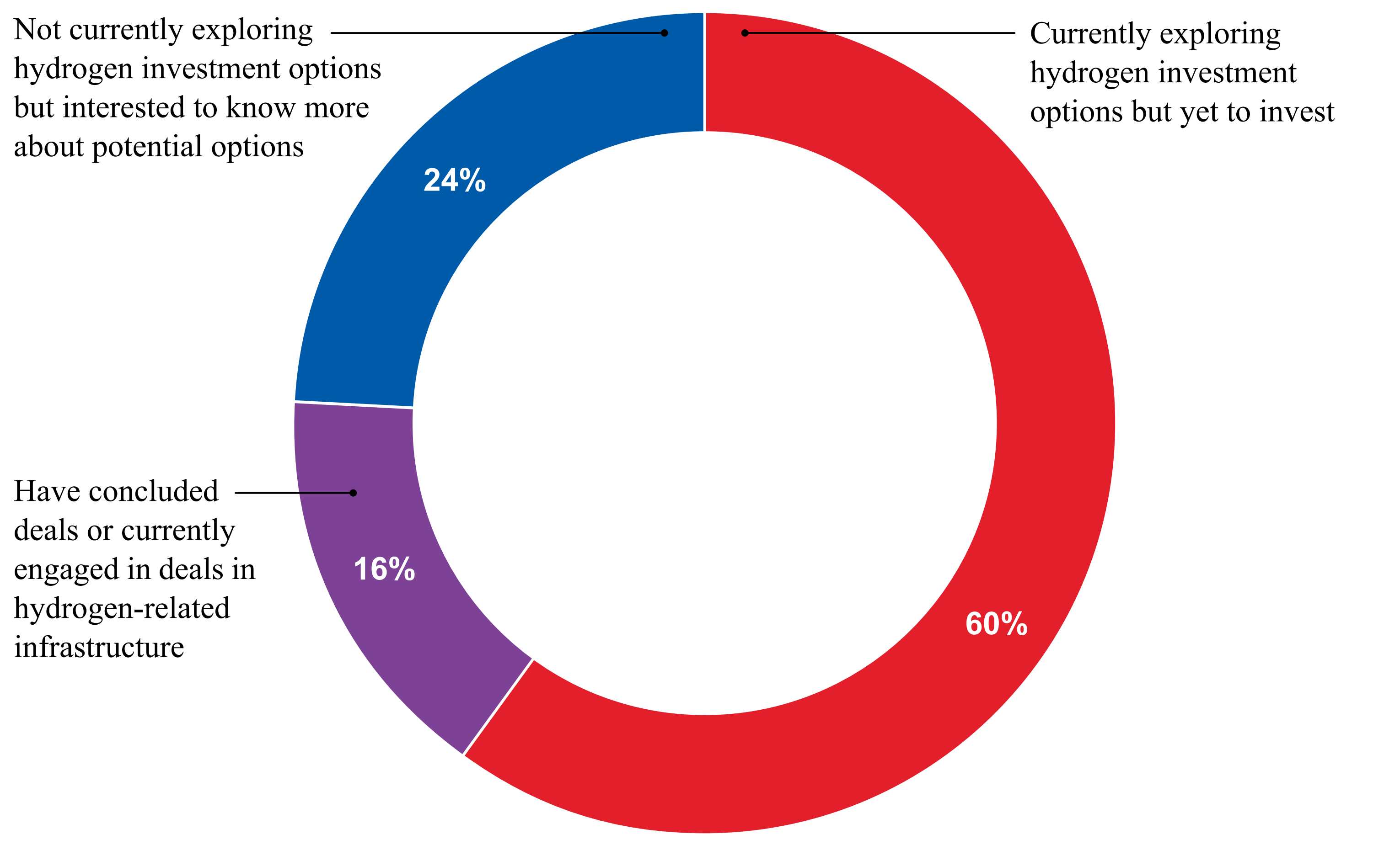
With over 200 hydrogen projects announced and total investments potentially equating to 1.4% of global energy funding, the conversation has shifted from why hydrogen to when and how much.

The momentum is predicted to continue with 75 countries announcing net-zero carbon ambitions and 30 with hydrogen specific strategies. External drivers, such as divestment from fossil fuels and responsible investment, makes low carbon hydrogen an attractive asset class for investors with significant growth potential.

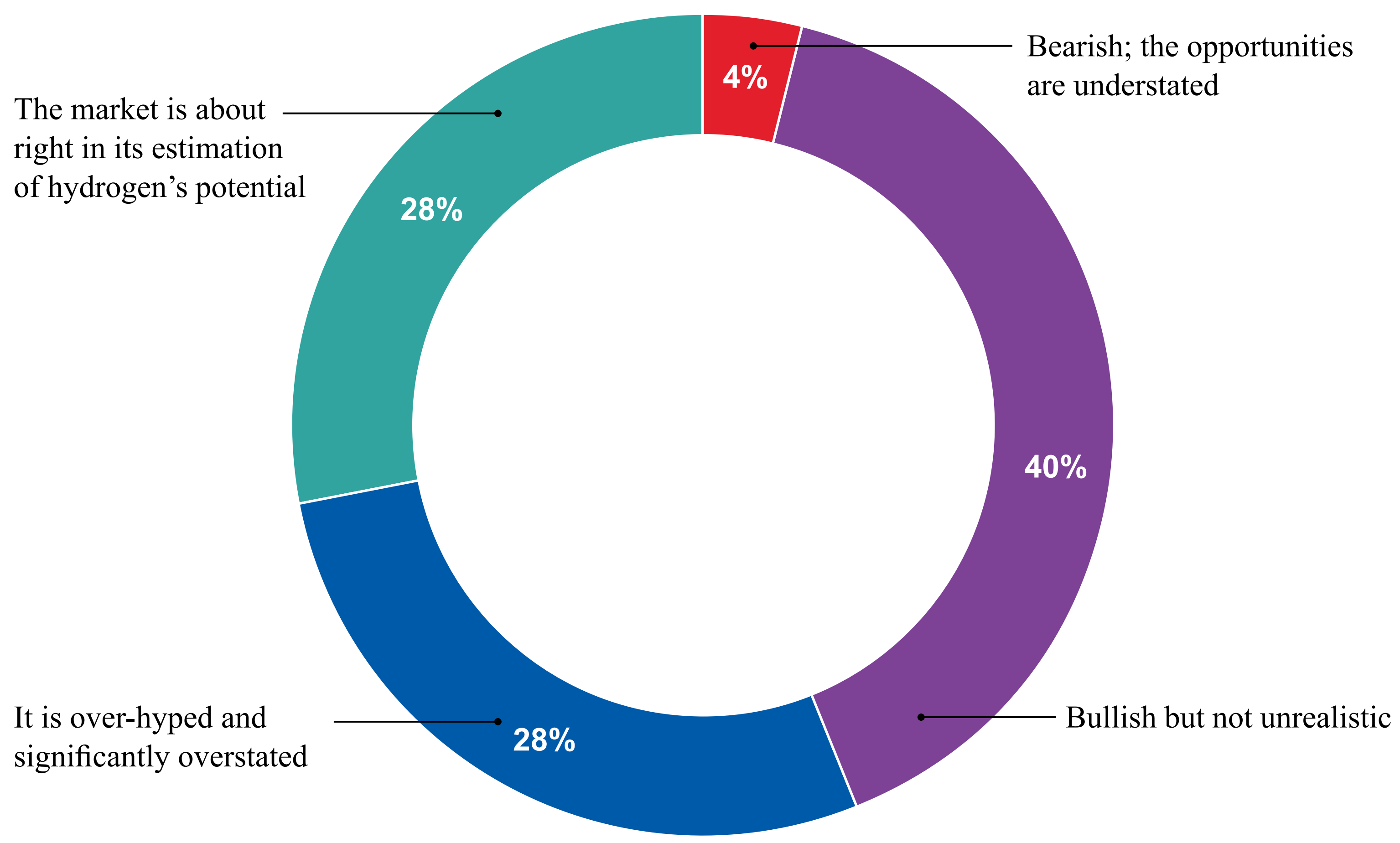
Later in this report, we'll explore how hydrogen touches a range of sectors that have traditionally operated as silos – energy, transport, industry. This highlights hydrogen's potential for "sector-coupling", which will require whole-systems thinking and new approaches for policy and regulation. The under-pinning infrastructure varies across the value chain and will require significant investment if hydrogen is going to live up to its potential for decarbonisation.

> "When it comes to investment, it really comes down to having a clear understanding of risk and return. If there is a remuneration framework that makes it attractive, people will invest. But people don't invest on government announcements of plans."
>
> North American Pension Fund

What is the status of your organisation's approach to investment in hydrogen-related infrastructure?



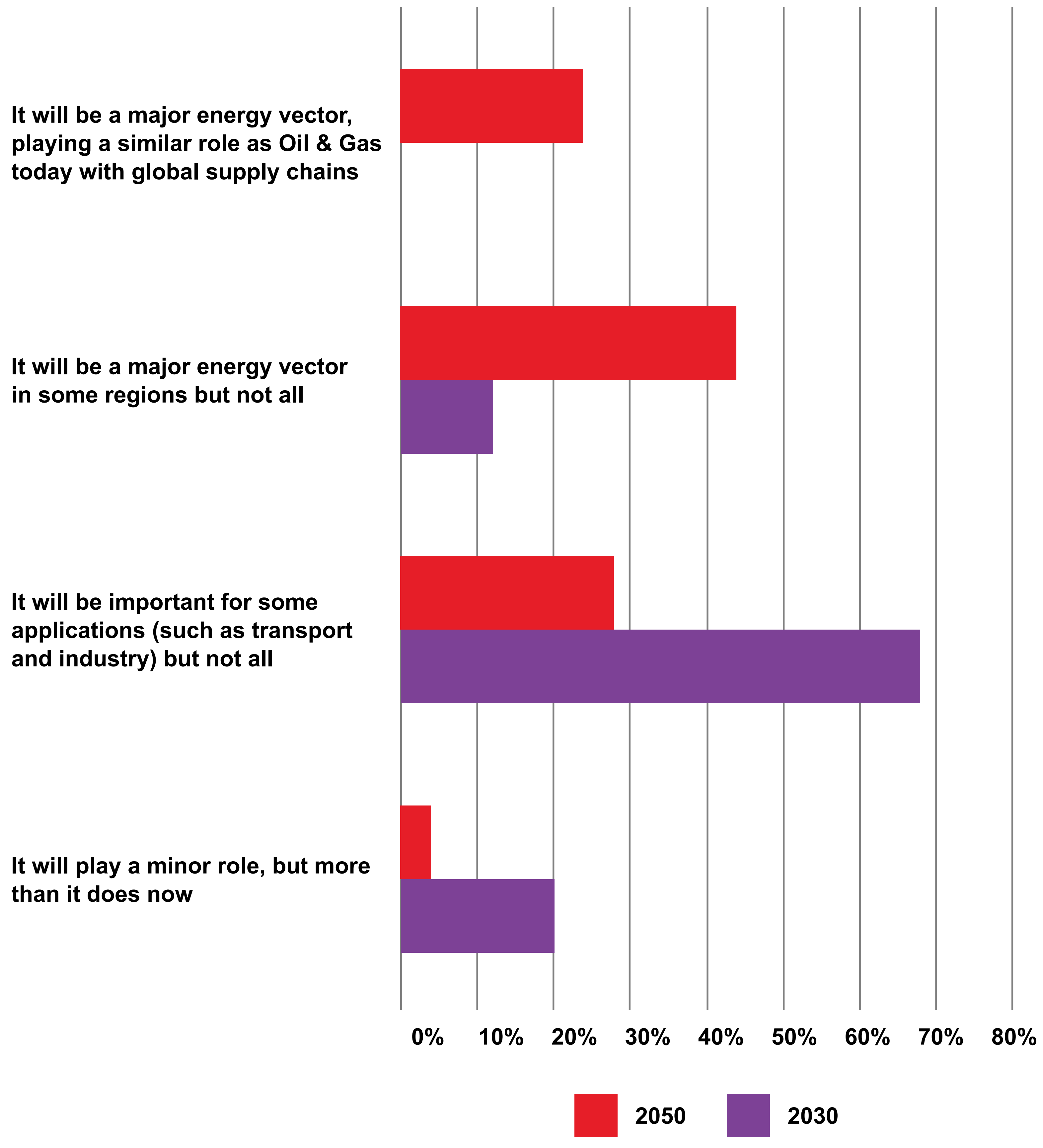
What is your impression of the market's current attitude towards investment in hydrogen-related infrastructure?



The survey of GIIA members found that although only 16% of investors have currently concluded deals or are currently engaged in hydrogen-related infrastructure, almost 70% believe hydrogen will be important for some applications by 2030 and 90% believe hydrogen will play some sort of role in the energy system.

This demonstrates the disparity between current investment activity and potential for future growth. Policy and regulatory intervention is urgently needed to catalyse private sector investment in the coming months and years if the hydrogen is going to play its necessary part in the decarbonisation of our economy.

How much of a role do you think hydrogen will play in the global energy system?



Momentum building as governments across world commit to hydrogen strategies

Governments around the world have announced strategies for developing the hydrogen market, but regulatory support is needed now to make it cost-effective and fulfil its huge potential.

Investments in the clean energy sector typically run for approximately 25 years. Therefore, governments and investors must act soon for the vast potential of the hydrogen economy to be unlocked by 2050.

It's clear that in applications where low carbon hydrogen could replace fossil fuel sources, it faces significant headwinds from a cost perspective.

In much the same way that solar and wind technologies needed government intervention to drive investment and adoption in the early 2000s, the hydrogen economy will require similar policy and regulatory support in the coming years. Moreover, in the case of hydrogen, policymakers have the benefit of lessons learned in the renewable sector.

Following on from their Nationally Determined Contributions under the Paris Agreement, governments around the world have begun to develop strategies for developing the hydrogen market accompanied by concrete proposals for policy and regulatory support mechanisms to enable that market.

This is a rapidly developing area and this section provides a snapshot that will likely be outdated by the time the ink dries on the page, but it does provide an impression of the significant momentum that is beginning to build, which is encouraging investors.

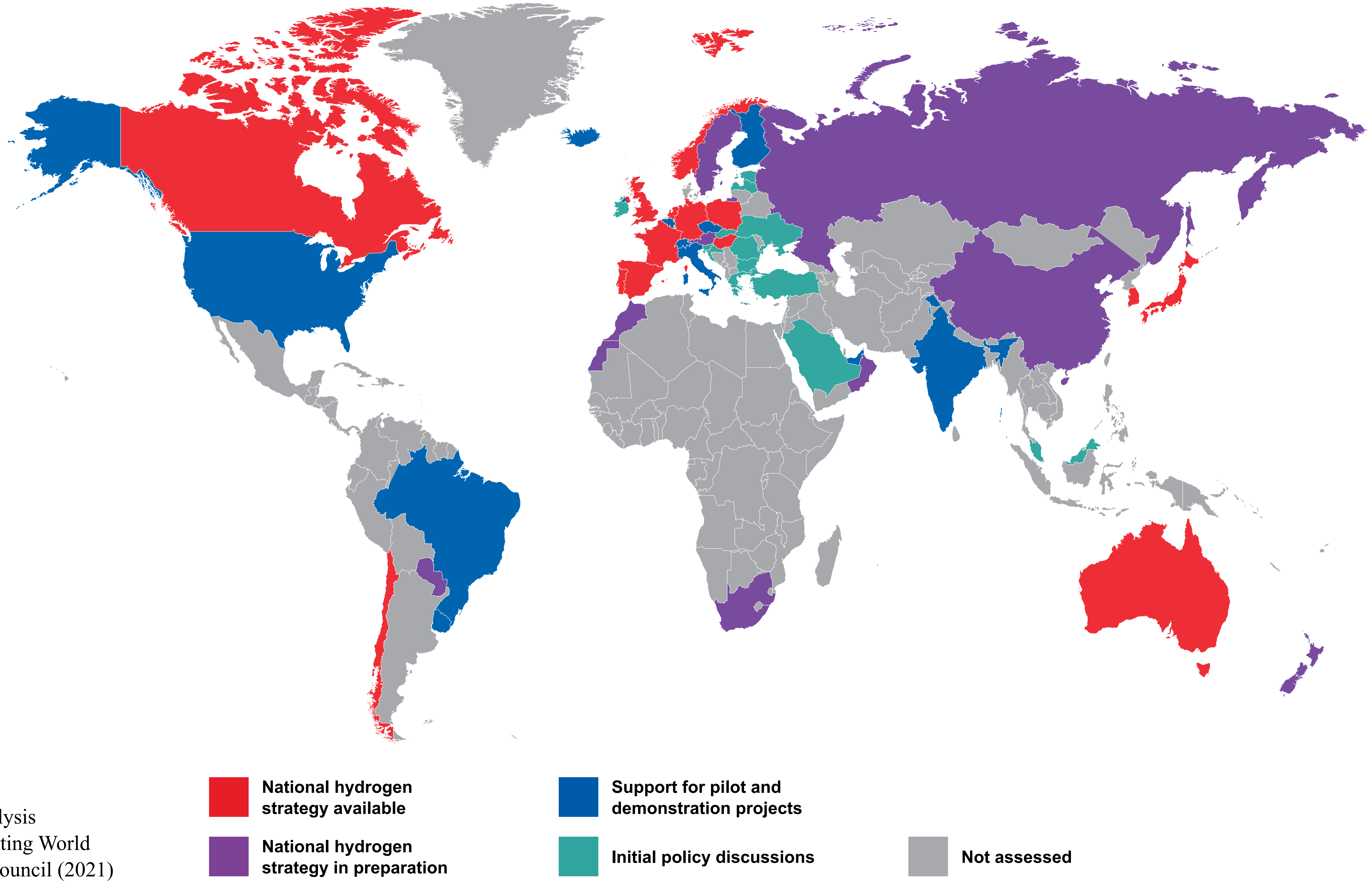
However investors need to see more than high-level strategies; they are calling for time-bound plans with measurable goals, backed by clear financial support mechanisms. The following sections of this report describe what is required, taking each stage of the value chain in turn.

$1/kg
is the price of clean hydrogen the United States' 'Hydrogen Shot' government initiative aims to reduce to within the next decade.

40GW
electrolyser capacity target set by the European Union for 2030.

World's 1st
'Hydrogen law' passed in South Korea.

AU$370m
in support for Australia's hydrogen strategy.



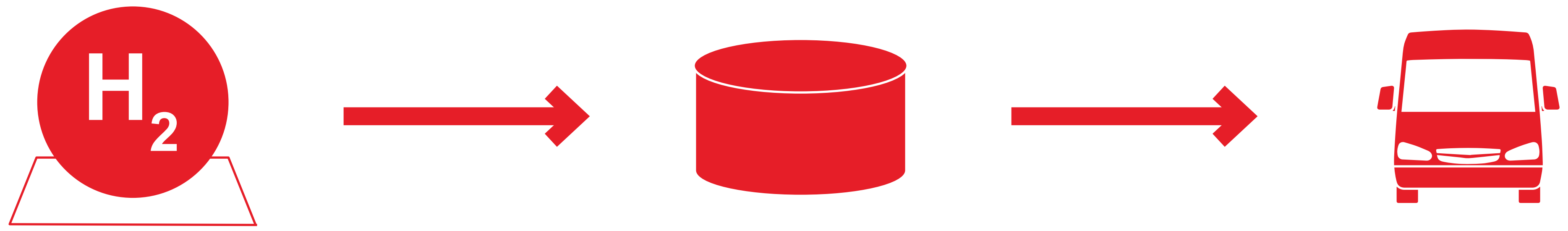
Arup analysis incorporating World Energy Council (2021)

The opportunities for private sector investment across the hydrogen value chain

An overview of the hydrogen value chain

When it comes to hydrogen infrastructure, it is useful to take each stage in the value chain individually because the issues are unique in each.

Therefore, the next few sections of this report present the opinions of investors, analyse the characteristics of the technologies involved and discuss the barriers and enablers for investment in production, end-use and transport and storage (T&S) respectively.



Production

– Fossil fuels with carbon capture

– Methane pyrolysis

– Electrolysis

Transport and storage

– Piping systems

– Storage

– As a compressed gas or cryogenic liquid

– Liquid organic hydrogen carriers

– Metal hydrides

– Other molecules (e.g. ammonia, methanol)

End-use

– Refineries and chemical production

– Industrial processes requiring high temperatures

– Transport

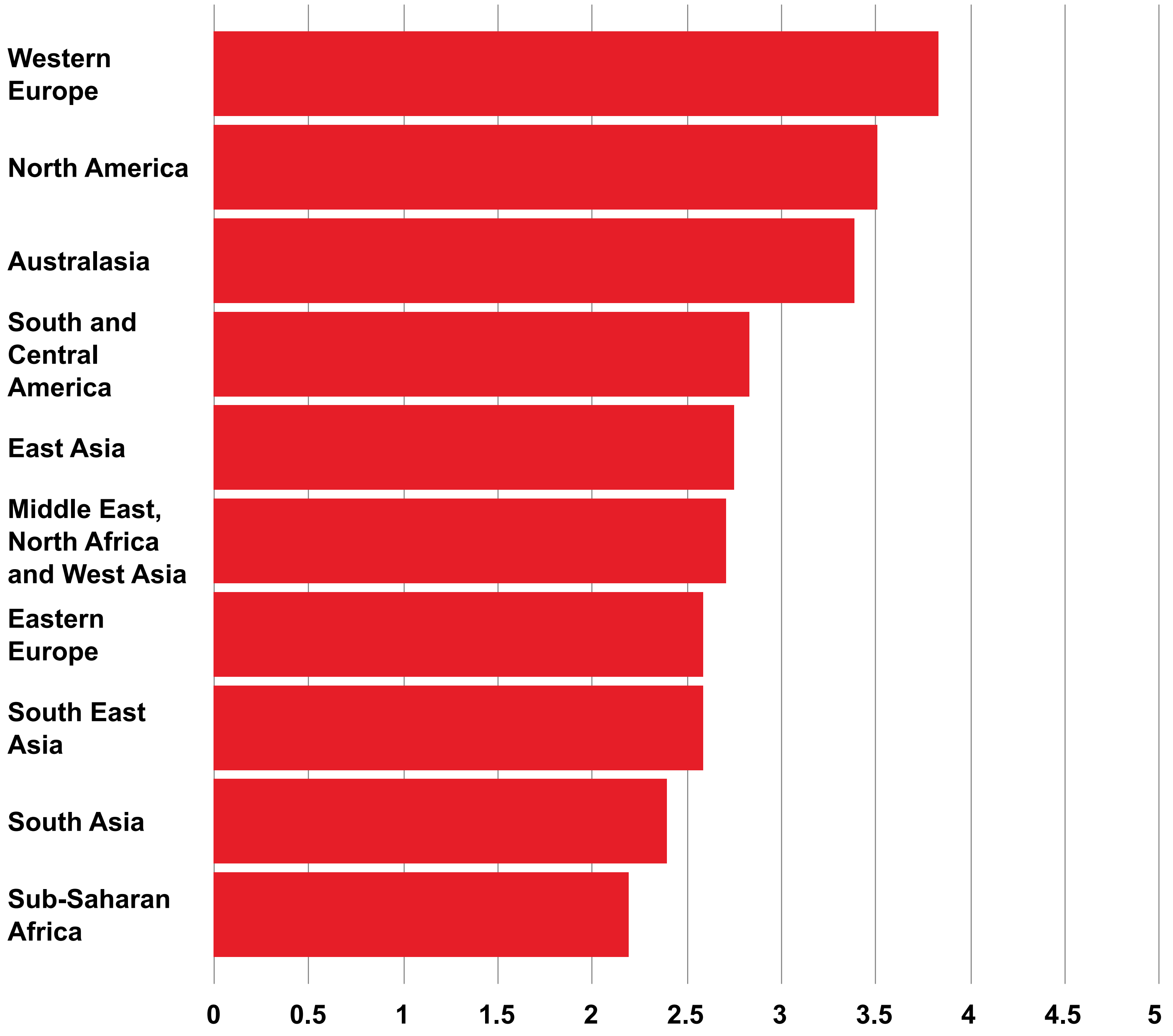
– Heating

– Electricity generation and storage

Production infrastructure - Clean hydrogen must show its true colours

The private sector is poised to invest heavily in low carbon hydrogen production - but concerned by uncertainty of future revenue streams.

Investor opinions about hydrogen production infrastructure (rating out of 5)



Global hydrogen production in 2020 was estimated to be around 3,000 TWh.

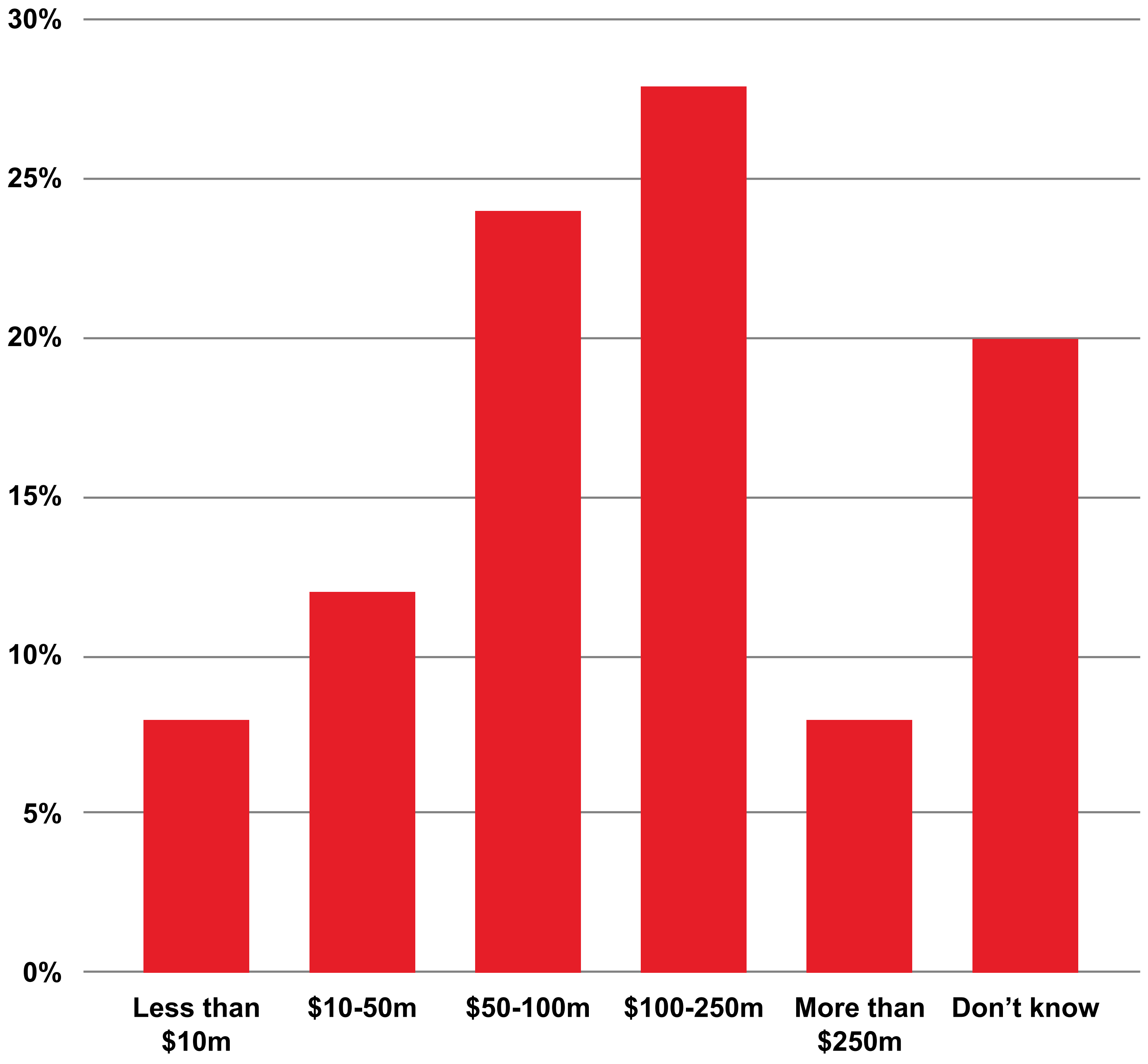
However, nearly all of this (c. 98%) was produced from fossil fuels with significant GHG emissions. For hydrogen to fulfil its potential as a low carbon energy vector, adoption of alternative low carbon production pathways will be required.

This section opens with the opinions of investors about low carbon hydrogen production infrastructure, then discusses the status of currently available technologies and concludes with barriers to investment and how these could be addressed.

One in five respondents to the survey admitted that they were unsure of how much investment their organisation would make in hydrogen production infrastructure by 2025. Of the 80% of respondents that indicated they expected their organisation would be investing into hydrogen production before 2025, the highest proportion are expecting to invest between $100 and $250m by 2025. This is consistent with some of the trends in hydrogen funds that are currently being set up, which are initially targeting up to approximately $250m but with plans to expand beyond that in the future.

This demonstrates that private sector capital is poised to invest in hydrogen production infrastructure, but investors are reluctant to commit funds without more certainty about future revenue streams. The following pages describe the low carbon hydrogen production technologies that are currently available and discusses the possible interventions to overcome the barriers holding back investment.

Scale of expected investment by 2025 - Production



What are the hydrogen production technologies?

Many methods are available, but the full lifecycle of low carbon hydrogen production must be factored in to maximise emission reduction.

Multiple hydrogen production technologies and pathways are available, each with different characteristics and associated lifecycle emissions. These are often categorised according to the “colour” of hydrogen produced. Each colour represents a different production pathway but this method of categorisation, although catchy, can be ambiguous and overly simplistic. However, labelling of production pathways by colour has become common when discussing hydrogen, so for ease of understanding this report uses the definitions listed to the right.

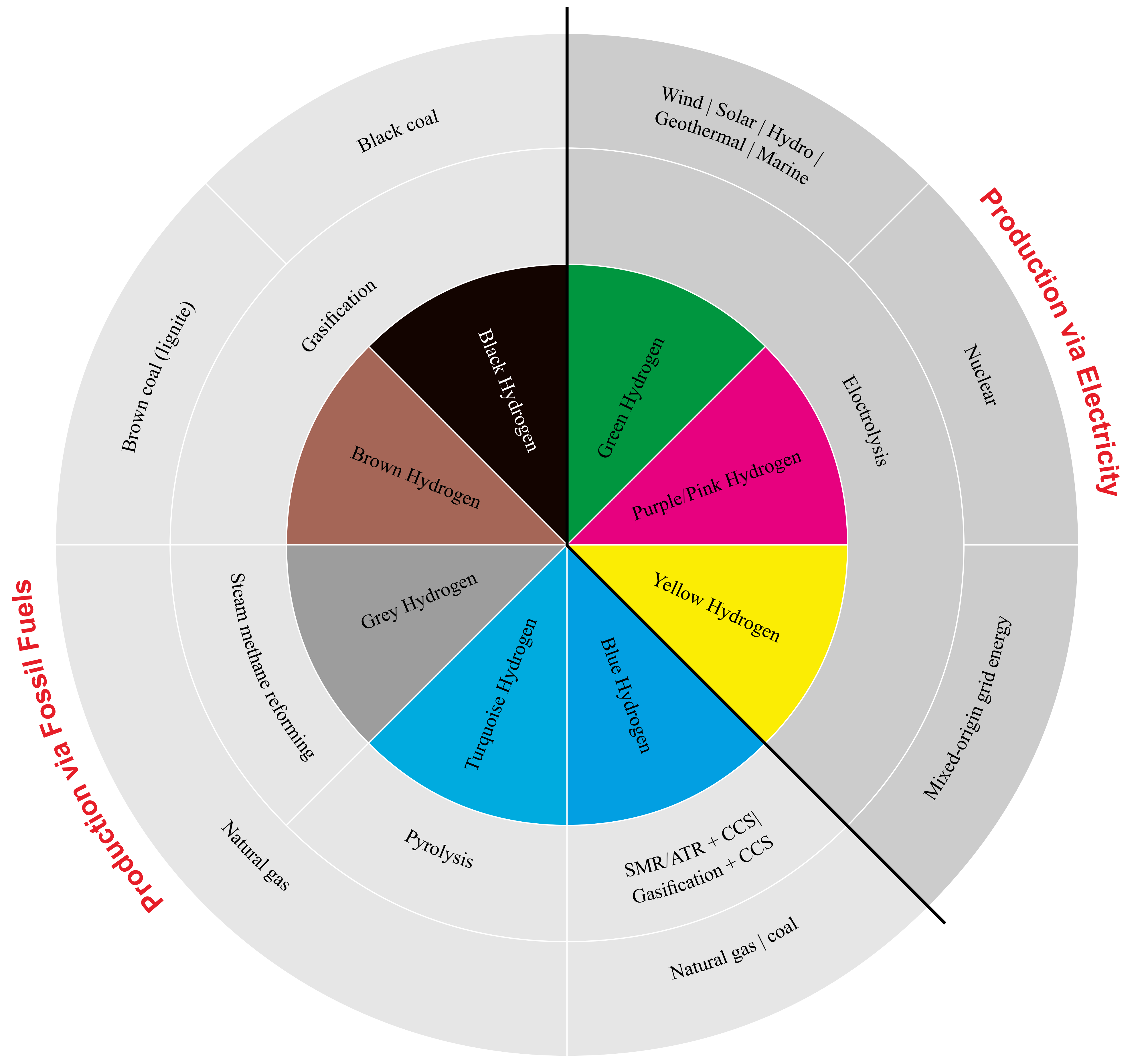
Approximately 98% of the world’s hydrogen is produced using unabated steam methane reforming (SMR) or coal gasification (grey, black and brown hydrogen), with only a small proportion produced by low carbon pathways. These are described in the paragraphs below.

98%

of the world’s hydrogen is currently produced using unabated fossil fuels.

Blue hydrogen

Blue hydrogen encompasses hydrogen production pathways from fossil fuels coupled with carbon capture and storage (CCS) technologies where carbon dioxide is captured and permanently sequestrated. Blue hydrogen production has been proposed by some stakeholders as an enabler for green production pathways, allowing the sector to scale up at lower cost. Although this view continues to be hotly debated there is broad consensus that with current technologies, blue hydrogen can be built at the scale of hundreds of megawatts at a lower cost than green hydrogen in the next few years.



There is a range of new blue hydrogen technologies that could be deployed, each with their own characteristics and carbon capture rates. These include SMR coupled with CCS, partial oxidation and autothermal reforming (a combination of SMR and partial oxidation) technologies. In addition, it is possible to retrofit carbon capture equipment at existing plants (subject to land availability and feasibility studies) which has potential to reduce emissions from current production processes. This comes at significant cost and can reduce the energy efficiency of the SMR process by up to 15%.

Turquoise hydrogen

Hydrogen produced from methane pyrolysis, also referred to as methane cracking, is known as turquoise hydrogen whereby natural gas or biomethane is split into hydrogen and carbon. Some of the carbon is released as carbon dioxide and needs to be captured while a proportion comes out in solid form, known as "carbon black". This novel alternative has potential to be a low carbon process if renewable electricity is used to drive pyrolysis, or potentially net carbon negative over the lifecycle if biomethane is used as a feedstock instead of natural gas.

Green, pink and yellow hydrogen

Electrolysis is another commercially available hydrogen production technology, which uses electricity to split water molecules into hydrogen and oxygen. If renewable electricity is used in this process the resultant product is labelled as green hydrogen, whereas nuclear-powered electrolysis is called pink or purple hydrogen. For yellow hydrogen, where a blend of electricity sources from the grid is used, the carbon emissions of this will depend on the carbon intensity of the grid mix.

Multiple electrolyser technologies are available, with alkaline types having been around the longest at commercial scale. Proton exchange membrane (PEM) electrolysers have recently reached megawatt scale in commercial applications too. Currently, alkaline electrolysers generally have lower capital costs and have slightly higher conversion efficiencies than their PEM equivalents, but these gaps are expected to narrow in the coming years. With these technologies proven at industrial scale, the focus of manufacturers is to scale up production quickly and develop larger projects to achieve economies of scale and meet anticipated increases in demand precipitated by ambitious production targets announced in national hydrogen strategies. Other electrolyser technologies are making their way up the technology readiness ladder to prototype stage, with the frontrunners being solid oxide and anion exchange membrane designs.

Green hydrogen production is recognised as a promising long-term solution to facilitate emission reductions due to its ability to enable sector coupling and therefore facilitate flexibility within integrated energy systems and encourage increased use of renewable sources of electricity.

While green hydrogen dominates discussions about electrolysis-based pathways, nuclear-powered production also holds promise. Nuclear power plants produce electricity and heat in a stable manner, which means that they can be paired with electrolysers (e.g. solid oxide) that operate at high temperatures and provide increased efficiencies. The baseload nature of nuclear power also means that the electrolysers can operate most of the time, improving the economics over those connected to intermittent supplies from renewables. Moreover, the nuclear option can provide production at gigawatt-scale. However, the sector is heavily regulated, so developing a nuclear hydrogen plant concept is likely to take years and the high capital costs of nuclear plants will also pose a challenge to competing with other production pathways.

Potential for emissions reduction should be considered on a lifecycle basis

Emission intensities, defined as the level of GHG emissions per kg of hydrogen produced, vary between production pathways and are region dependent. For the hydrogen ecosystem to evolve, a lifecycle analysis should be conducted to understand the full GHG emissions impact of each solution. For example, when comparing the emissions of blue and turquoise hydrogen against other pathways, fugitive emissions of natural gas (methane) in the supply chain need to be factored in because they can significantly undermine the decarbonisation credentials if they are not carefully monitored and regulated.

In addition to the emissions from the feedstock supply chain, other aspects of the product lifecycle need to be included too. For example, the emissions associated with the manufacture of the plant and equipment as well as the emissions from construction.

Depending on where you draw the scope boundaries of the analysis, the results can be vary widely. For example, if you include the emissions associated with the manufacture and installation of solar panels or wind turbines for green hydrogen production, then the lifecycle emissions can be higher than is commonly assumed.

All these aspects need to be considered by policy makers when deciding whether to provide support to specific technologies and the eligibility criteria that will apply to them.

> "Cases for much larger amounts of production that we are seeing are for existing users of grey hydrogen that want to replace grey hydrogen with green and/or blue."
>
> Global Fund Manager

What factors will influence the success of low carbon hydrogen production?

Reducing cost through location, technology, transport and storage.

Despite the positive press about low carbon hydrogen, fossil-derived hydrogen with carbon capture and electrolysis-based pathways still have a long way to go before they reach the production volumes required to provide meaningful carbon emissions. However, there is also significant scope to improve designs through innovation and learning by doing, as well as reducing costs through economies of scale.

18-24 kg

of water per kg of hydrogen is needed for water electrolysis

13-18 kg

of water per kg for blue hydrogen

One consideration that is relevant to all production pathways, but to varying degrees, is the significant amount of water that is consumed. For example, between 18 and 24 litres of water is needed for every kg of hydrogen produced by electrolysis depending on the source and quality (this goes through a treatment process resulting in about 9 litres of per water per kg hydrogen). The blue hydrogen processes requires slightly less (13-18 litres per kg hydrogen) but the purity doesn't need to be as high as for electrolysis. Therefore, the availability of water needs to be carefully considered when siting hydrogen production plants. One solution is to locate plants near the coast so that seawater can be used after treatment in a desalination plant, but then there needs to be an environmentally friendly method of disposing of the waste product (including brine).

Some of the investors interviewed for this report indicated scepticism about carbon capture technology, citing the inability of the technology to live up to its promises in the power sector in the past. Despite its chequered history, carbon capture technology has been applied successfully in other commercial applications (e.g. enhanced oil recovery), albeit at lower capture rates than are forecast for state-of-the-art blue hydrogen plants. The world's first large scale blue hydrogen plants are at advanced stages of project development and are expected to become operational by the mid-2020s. It is hoped that these plants will demonstrate that it is possible to capture more than 90% of the carbon dioxide produced in the process.

Once blue hydrogen technology is proven at industrial scale, the Global CCS Institute states that the costs of production will be influenced by the following key factors:

- Differences in fuel costs: Production costs are capex driven in locations with low-cost gas (overall cost is $1.50/kg hydrogen) and driven by a high gas price otherwise (overall cost is $2.40/kg hydrogen).
- Technology selection: Coal gasification with CCS is deemed to be more capital intensive compared to steam methane reforming with CCS.
- The cost of transport and storage of CO_2: Differing production pathways require varying amounts of CO_2. Therefore, carbon-intensive pathways will be more sensitive to CO_2 transport and storage costs than others.

Turquoise hydrogen technology is at demonstration scale, with private companies marketing solutions and research institutions such as Netherlands Organisation for Applied Scientific Research and the Karlsruhe Institute of Technology working on a pilot plant. Organisations in the Americas and Europe are emerging as early leaders in the technology.

Countries across the globe are rapidly increasing investments to scale up green hydrogen production and capitalise on advantageous wind and solar resources (e.g., Chile, Spain, UK, Sweden). Projects are increasingly financed by public-private enterprise models as demonstrated by the collaboration between the Japanese Government and Tohoku Electric, Toshiba, and Itwatani, funding Fukushima Hydrogen Energy Research Field, producing 900 tonnes of hydrogen per year. The production costs of green hydrogen are heavily influenced by the capital cost of the electrolysers and the price of the renewable electricity powering them. Hence cost estimates vary, but the Hydrogen Council gives a range of between $4 and $6 per kg of green hydrogen in 2020 with expectations of about a 60% reduction to this by 2030.

Advances in electrolysis technologies are dependent on optimising the following technical parameters:

- Improving the stack design and cell composition can facilitate higher electrolyser efficiencies and therefore lower electricity consumption, in addition to increased durability increasing the lifetime of the stack.
- Increasing module size could have significant cost reduction potential through enabling economies of scale for balance of plant components, reducing plant footprint and associated capital costs.
- Improved electrolyser response time, and therefore the ability for the system to reach its maximum operating power, can result in reduced operating costs.
- Reductions in water consumption and research into using seawater directly will make electrolysers more attractive for locations with limited water access.

What are the barriers and enablers for investment in production infrastructure?

Coordination between institutions, national governments and industries key to enabling potential of the hydrogen economy to be recognised.

This section concludes by discussing some of the barriers to investment in hydrogen production infrastructure and the range of policy enablers to overcome these barriers.

Preferences for hydrogen production through various pathways are evident across the globe. While the European Union has announced its target of 40 GW of installed electrolyser capacity by 2030 and its preference for green hydrogen, countries such as South Korea, Japan and China have no preference for a particular solution and express a more diversified strategy encompassing grey, blue and green strategy as a mid to long-term solution.

Investors expressed “large regional differences between support from population and regulators” and coordination between institutions, national governments and industries is key to enable the potential of the hydrogen economy to be recognised. It is essential for the role of hydrogen to be clearly communicated to the industry and public, and, based on detailed analysis, its part in meeting emission targets.

Long-term incentives to overcome the cost gap

Incentives such as a contract-for-difference (CfD)-based model, with private sector backing or government schemes to ensure revenue certainty can increase confidence for first mover investors.

The UK’s hydrogen strategy for example, includes a proposal for a similar scheme to the CfD-based model, “designed to overcome the cost gap between low carbon hydrogen and fossil fuels”. This coupled with public-private sector collaboration is expected to drive private sector investments.

To increase production volumes and ensure acceptable return on investment and bankable investments, production tariffs such as a carbon contract for difference, auctions or a hybrid approach can be adopted. Governments can learn from a trial-and-error approach as demonstrated by China when setting an initial renewable (solar and wind projects) production tariff and using actions to “fine-tune” the scheme.

Reaching economic competitiveness is the greatest barrier for the scaling of green hydrogen production

This is driven by technological advances with the electrolysers, as well as costs of renewable electricity which could be 15% lower than current levels by 2030, with greatest potential in favourable locations with significant untapped resource potential in places like Australia, Chile, North Africa, and the Middle East.

It is important to account for the principle of additionality

Overbuilding the renewable supply encourages sector coupling and therefore an integrated energy system. Accounting for the principle of additionality ensures opportunities are not taken away from direct electrification and provides an opportunity to mitigate curtailment of intermittent renewable sources like wind and solar. Many governments are working on regulations to ensure that the renewables required for green hydrogen are in addition to those required for decarbonisation of the grid, but they need to be carefully designed to avoid distorting the market.

Tax and levy exemptions

Exemptions from electricity taxes and levies are common in policies designed to increase investment in clean technologies, with the United States being a good example. Expanding this approach to include electrolysers may provide more confidence that green hydrogen has a significant role to play in the future energy system. This exemption from electricity tax is already being applied in Norway, France, and the Netherlands, for example.

Grants and innovation funds needed to support R&D activities

Grants have already spurred the growth rate of low carbon technologies. This is evident across the world, with notable examples from the EU Innovation Fund, investing $139m into 32 small innovative projects and applications recently opening for Japan’s Green Innovation Fund, with a total investment of $18bn.

Investors also indicated that capital financing mechanisms have potential to fuel support for low carbon technologies. This could be implemented in the form of government capital grants with certain criteria or conditions that must be met to benefit both parties involved, capital guarantees, equity-loan hybrids or schemes linking utilisation rates to government payment guarantees. These mechanisms could in turn reduce the cost of capital for low carbon hydrogen investments.

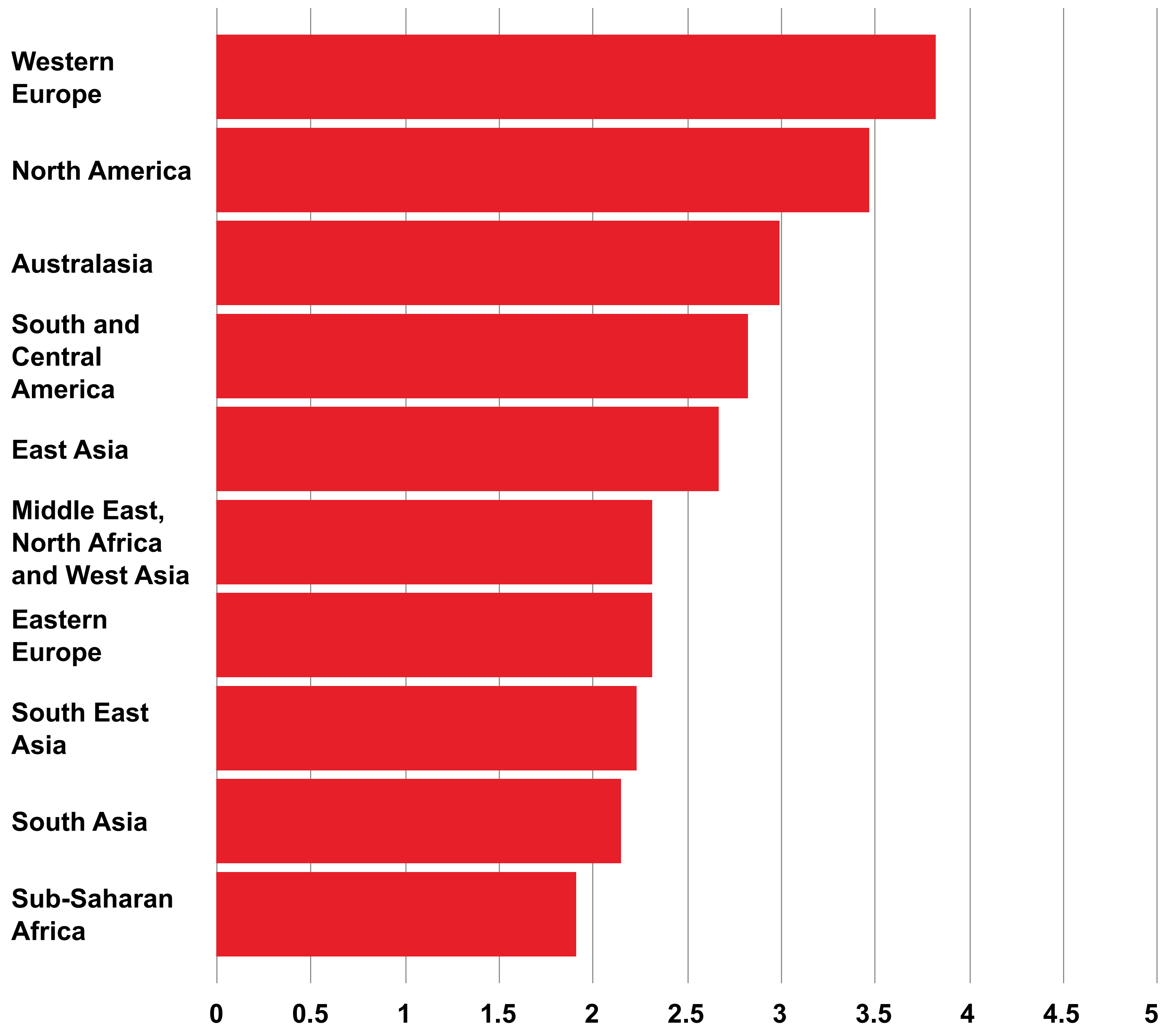
Transparent and robust certification and labelling system

Considering it is not possible from a chemical perspective to differentiate high-carbon hydrogen from low carbon production methods, a key aspect of implementing these measures will be a transparent and robust certification and labelling system as demonstrated by CertifyHy in Europe and the Low Carbon Fuel Standard in California.

End-use infrastructure - Creating demand with a targeted approach

Hydrogen has the potential to be used as a low carbon alternative in many different end-use applications but these need to be viewed considering the alternatives, which might provide a cheaper or more efficient approach to decarbonisation.

The regions investors have most confidence in (rating out of 5)



Most confidence in Western Europe and North America

Investors are most bullish about Western Europe and North America when it comes to end-use infrastructure. Australasia has high potential, but there is some uncertainty about how the market might proceed. On the other end of the scale, investors are most negative about Africa. There is a measure of ambivalence about the prospects for Asia, Eastern Europe and South and Central America.

Investors remain uncertain about level of commitment to end-use infrastructure development

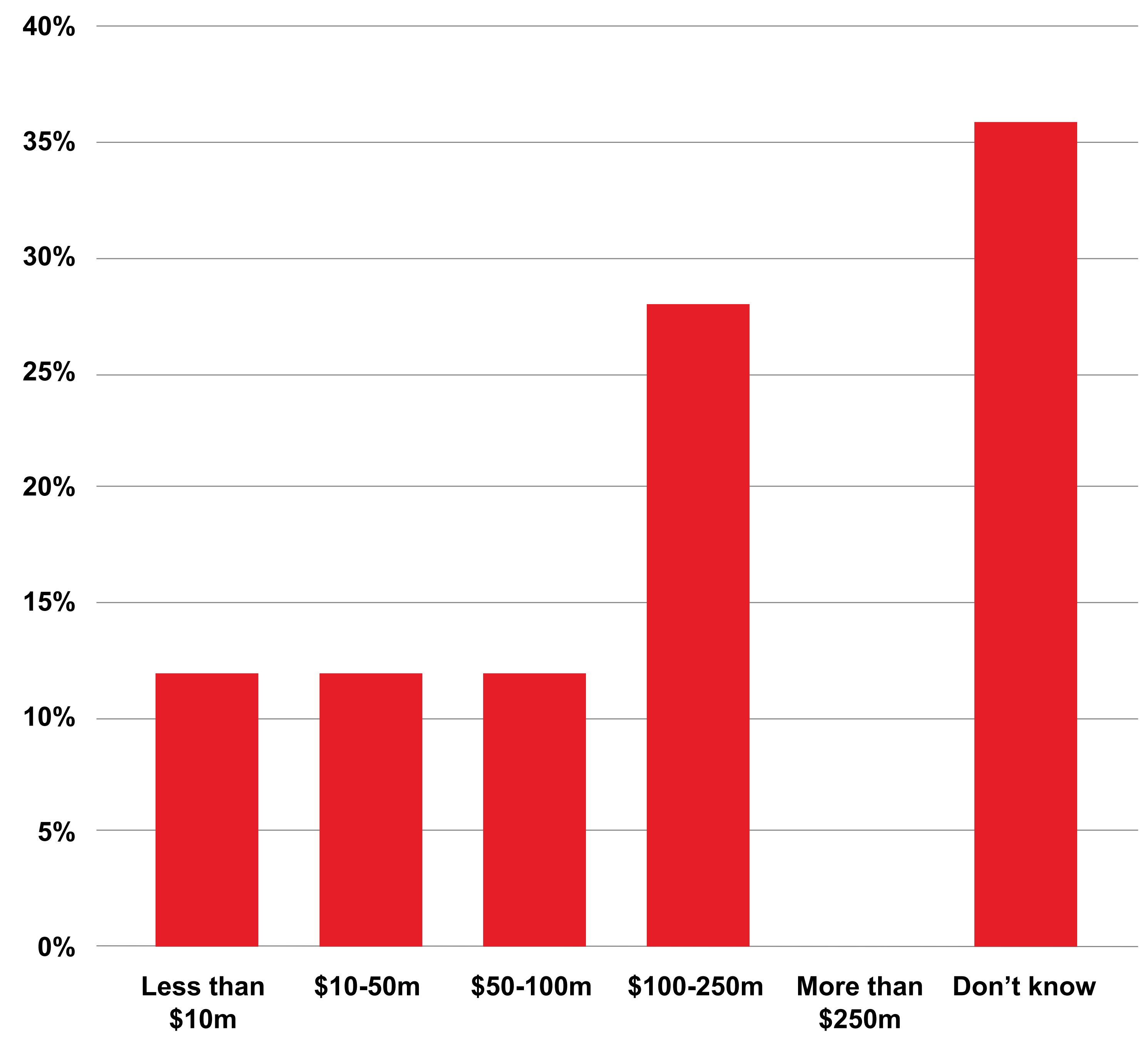
More than a third of survey respondents admitted that they didn't have an idea of how much their organisation would invest in end-use infrastructure by 2025 – the highest rate of the six categories.

Of those that were able to give an estimate, none were aiming for more than $250m and nearly half estimated that it would be between $100m and 250m.

In contrast to production and T&S infrastructure, investors seem to be most uncertain about investment in end-use infrastructure and the expected scale of investment is generally lower. This probably reflects some of the uncertainty about the end-use sectors where hydrogen will be most appealing and an absence of direction provided by policy-makers and regulators. This could be because the end-use applications cover a wide range of industries that are governed and regulated by different agencies, so a joined-up strategy is lacking.

This section of the report will discuss the various end-use options and highlight what governments and regulators can do to encourage investment.

Scale of expected investment by 2025 - End-use



What applications of hydrogen appear to offer the lowest risk for investors?

An initial focus on applications with a high marginal cost of greenhouse gas abatement can offer lowest risk of future regret.

The feasible applications for hydrogen will vary by location, depending on the make-up of the economy and existing energy infrastructure (e.g. whether an existing gas grid is present).

There is growing consensus that in general, hydrogen is best suited to decarbonise applications where direct electrification with renewable energy is not feasible. These have often been grouped under the banner of "harder-to-abate" sectors, but this nomenclature can be unhelpful and self-defeating.

For some applications, there continues to be some debate about the point where electrification becomes infeasible and a hydrogen-based solution is preferred (e.g. road freight). However, there are some applications where electrification is clearly not feasible and where low carbon hydrogen* (and its derivatives) is the preferred solution, including the following:

- Processes where unabated fossil-derived hydrogen is currently used:
  - Refineries
  - Production of chemicals such as ammonia (and by extension, fertiliser) and methanol
- Processes requiring high temperature heat where fossil fuels are currently used, including steel and cement production
- Sustainable aviation fuels
- Fuels for maritime transport.

As the market for hydrogen grows from a relatively low base, it makes sense to focus initial efforts on these applications where the marginal cost of GHG abatement is high, because this is where there is the lowest potential for future regrets.

There are other applications for hydrogen as a decarbonisation vector where direct electrification is technically feasible, but where the best solution depends on local conditions. The case for these tends to be nuanced and generally more contentious. They include the following:

- Heating – residential, commercial and light industry
- Medium and heavy road vehicles
- Small vessels (e.g. ferries, tugs and barges)
- Rail
- Electricity generation and energy storage.

The relative competitiveness of hydrogen with alternative decarbonisation measures in these contentious applications will be fluid over time as technologies advance and mature at different speeds, and indeed as new solutions emerge. Hence technology risks are likely to be higher in these applications and will require a higher level of scrutiny when considering investments.

These applications are discussed in more detail below.

Heating – Hydrogen blending could be first step

From a technical perspective, the most efficient route to decarbonising space heating is using heat pumps powered by renewable electricity. However, there are other factors that need to be considered as well.

Considering the low turnover in building stock, targets for decarbonisation are on a relatively short timeframe. This means that decarbonisation will require retrofitting low carbon heating solutions to existing buildings along with improvements to energy efficiency. Since there is such a wide range of building types and locations across the world, decarbonisation is likely to take different forms in different applications. In places where there is an existing connection to a gas network and limited space to install the larger radiators that are usually required for heat pumps, it could make more sense to convert the existing appliances to operate on hydrogen.

There is an opportunity to blend hydrogen with natural gas up to about 20% on a volume basis (this is about 7% on an energy basis), but thereafter a full conversion to hydrogen is required. In the short term, hydrogen blending could be a first step towards decarbonisation of heat. This is discussed further in the next section where transport and storage infrastructure are considered.

* Throughout this section, 'hydrogen' is used as shorthand for hydrogen and hydrogen-derived fuels.

Medium and heavy road vehicles – Competing technologies pose risks

The main challenge with electric vehicles is that current commercially available battery technologies store a much smaller amount of energy per unit volume than petrol or diesel. This means that there is a trade-off between cargo storage and energy storage space on board for larger vehicles like trucks that need to travel longer distances.

Another consideration is battery recharging time, which typically takes longer than it would to refuel a hydrogen tank; however behavioural change and innovation can overcome this barrier.

Other direct electrification technologies are also being explored, like catenary power on motorways, but again these would be application specific.

It might be possible to use battery storage for other large vehicles that return to a depot fairly regularly (e.g. buses and refuse collection vehicles) but sometimes high power requirements (e.g. operation along a hilly route) might make batteries unsuitable.

Therefore, there is a role for hydrogen in some road transport applications where direct electrification is technically infeasible. In these applications, hydrogen could be used in fuel cell electric vehicles or in hydrogen combustion engines.

However, investment decisions in this segment of the market would need to be underpinned by a robust analysis of total cost of ownership, accounting for the specific conditions. Considering the various competing technologies, it is inherently more risky.

Small vessels – Hydrogen opportunities where batteries are not a suitable option

It is possible to electrify smaller vessels like tugboats, ferries and barges if they don't travel long distances. Electrification is well suited to applications where vessels can stop at moorings relatively frequently to recharge. However, there are applications where current battery technologies are not suitable for the vessel's duty cycle. For these use cases, hydrogen or a hydrogen-derived fuel like ammonia or methanol might be a better option.

These fuels can be used directly in a fuel cell or in internal combustion engines. In some cases, existing combustion engines can be retrofitted to burn ammonia or methanol, but the fuel storage and handling systems would need significant modifications or replacement. There are examples of hydrogen fuel cell vessels in operation on some vessels already (usually adapting a design from land transport), but fuel cells for ammonia and methanol are still under development.

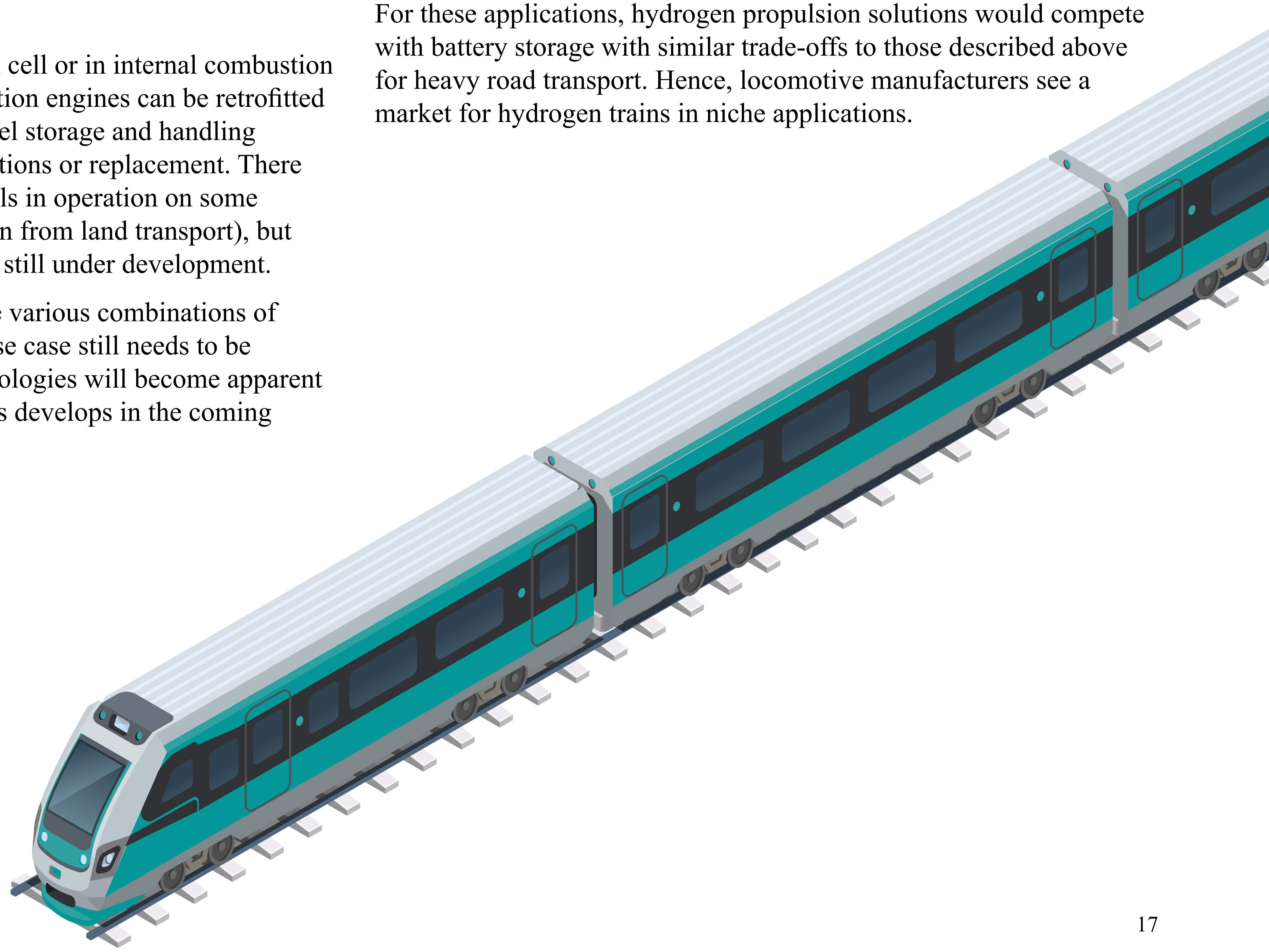
The advantages and disadvantages of the various combinations of fuels and propulsion methods for each use case still needs to be explored in detail, so the preferred technologies will become apparent as market for low carbon vessel solutions develops in the coming years.

Rail – A market for niche hydrogen trains

When starting from a clean sheet, the most obvious choice is to electrify rail transport with low carbon electricity. However, there are many sections of existing rail networks around the world that are not electrified and where fossil fuelled locomotives are still in operation.

In many cases, it would be prohibitively expensive or technically challenging to retrofit electrification to these sections.

For these applications, hydrogen propulsion solutions would compete with battery storage with similar trade-offs to those described above for heavy road transport. Hence, locomotive manufacturers see a market for hydrogen trains in niche applications.



Energy storage – Competition and inefficiencies increase the risks

If hydrogen is put into a suitable container and kept at an appropriate pressure and temperature, it can be used to store energy for long periods. Therefore, it can be used for longer duration storage in the electricity system to balance supply and demand.

There are various things that need to be considered when studying hydrogen as an energy storage option, including the scale and capital cost of the storage receptacle as well as the operating costs and energy losses in the associated processes. These depend on the scale and technology used to convert the hydrogen back to electricity, e.g. fuel cells, gas turbines, combustion engines or boilers.

The main drawback of using hydrogen for electricity storage is the relatively large amount of energy that is wasted at each stage of the thermodynamic cycle. The "round trip efficiency" of the cycle refers to the amount of useful electricity ultimately generated divided by the total energy required to produce, store and reconvert the hydrogen. For hydrogen, the round trip efficiency can be in the order of 30% depending on the application, whereas for lithium-ion batteries, the charge/discharge cycle is about 85-90% efficient.

There are multiple other types of energy storage technologies available as well, including pumped hydro, compressed or liquefied air storage, flywheels, supercapacitors and others. Considering the possible competition, investments that rely heavily on revenues from balancing demand and supply on the electricity grid need to be considered very carefully. The associated technology risks are likely to remain high.

A word about biofuels – A potential competitor

In most applications, hydrogen and its derivatives compete directly with fuels derived from biomass. From purely technical and financial perspectives, biofuels are often the superior option, especially because they can be used as "drop-in" replacements for fossil fuels without changing hardware for many applications. However, there would be significant social and environmental implications of widespread adoption of biofuels at the scale required to decarbonise the global economy.

It is not within the scope of this paper to explore the advantages and disadvantages of biofuels, but it should be noted as a potential competitor to hydrogen. The significant constraints in the supply of sustainable biomass mean that it should only be used in applications where there are very few alternatives (e.g. sustainable aviation fuels) or where there is a local abundance (e.g. isolated tropical islands with poor renewable potential). However, it could pose a risk to hydrogen investment particularly in jurisdictions with inadequate regulation and lax oversight of biomass supply chains.

Barriers and enablers for investment in end-use infrastructure

A "carrots and sticks" approach of incentives and disincentives can stimulate a move to low carbon alternatives.

This section on hydrogen end-use applications concludes by discussing some of the barriers to investment in end-use infrastructure and the range of policy enablers to overcome these barriers.

The main barrier to adoption of low carbon hydrogen in end-use applications is its high cost relative to incumbent carbon-intensive fuels. There is a simultaneous need to:

1. Stimulate adoption of low carbon alternatives (carrots) to reduce their costs, and
2. Internalise the costs of carbon from conventional fossil fuels through direct measures (sticks) including carbon tax to suit the application to increase the costs of high emission solutions.

The combination of carrots and sticks should be selected based on the characteristics of each jurisdiction based on the principles described in a later section.

Early focus on applications with limited alternatives

In the early stages of hydrogen market development, the focus should be on encouraging adoption in applications where there are limited alternatives for decarbonisation. This minimises the risk of future regrets, while allowing supply chains to be established and increase in scale.

The carrots and the sticks should be selected to suit the application and the local conditions.

A combination of the carrots below could be used (as appropriate for local conditions) to encourage adoption of hydrogen as a low carbon alternative to products with high associated carbon emissions:

– Grants for research, development and demonstration

– Clean fuel mandates (e.g. Low Carbon Fuel Standard in California)

– Public procurement quotas/mandates (e.g. a requirement to procure low carbon refuse collection vehicles or "green steel" for public sector buildings)

– Tax credits and/or exemptions.

A combination of the following sticks could be selected to internalise costs of carbon from products with high associated carbon emissions:

– Carbon taxes, including cap & trade mechanisms (e.g. Emission Trading Schemes)

– Bans on polluting technologies (e.g. Future ban on the sale of new petrol and diesel internal combustion engine vehicles announced in the UK)

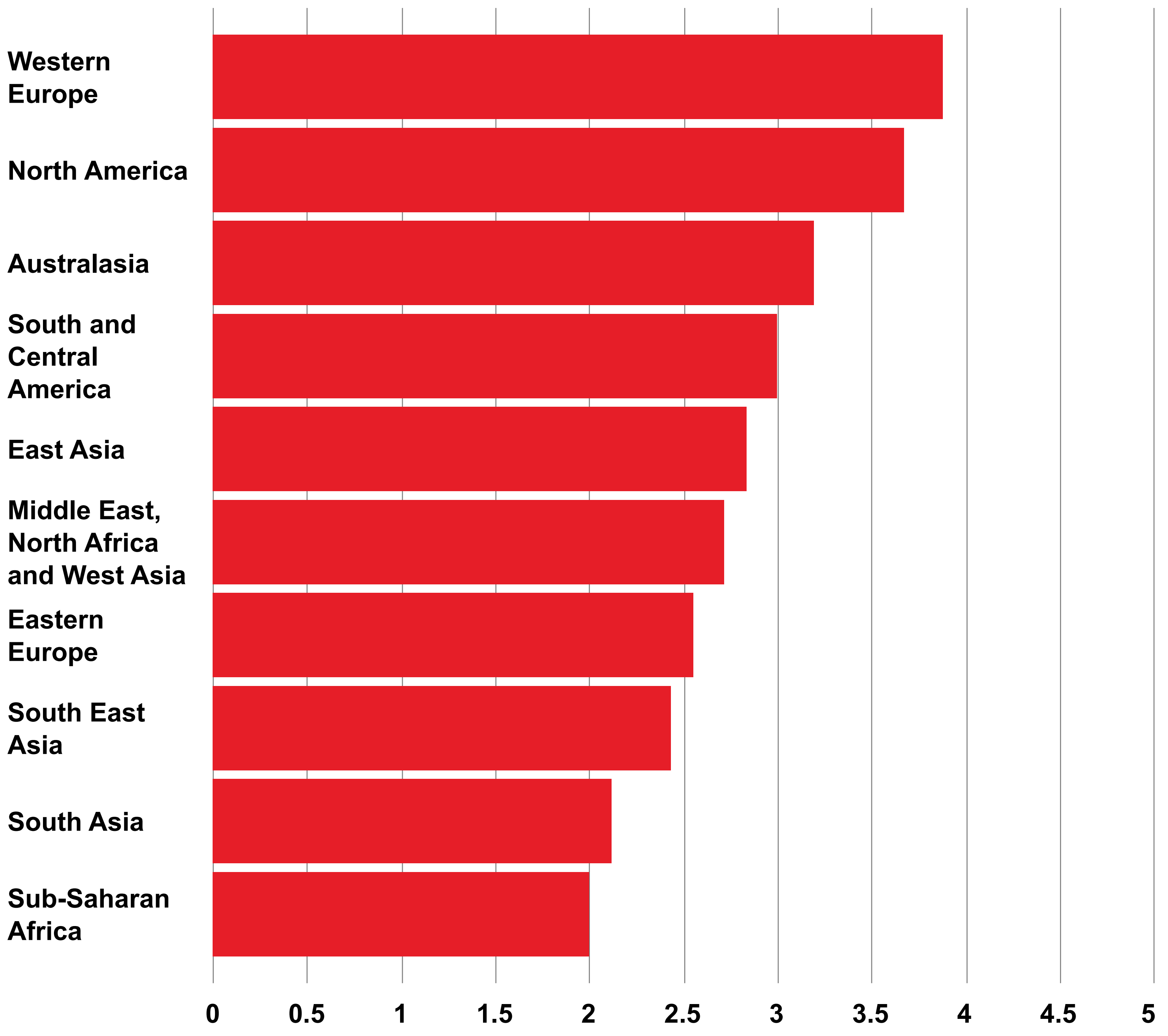
– Levies/taxes on existing carbon-intensive technologies and processes (e.g. tax on fossil-derived road fuels)

– Tariffs on imported products based on carbon content (e.g. European Union's proposed Carbon Border Adjustment Mechanism).

Transport and storage infrastructure - Connecting supply and demand

It is all very well to scale up production of low carbon hydrogen and stimulate demand for it in a range of sectors, but the hydrogen economy will never emerge if there is no cost-effective method of getting the hydrogen from the producers to the consumers.

The regions investors have most confidence in (rating out of 5)

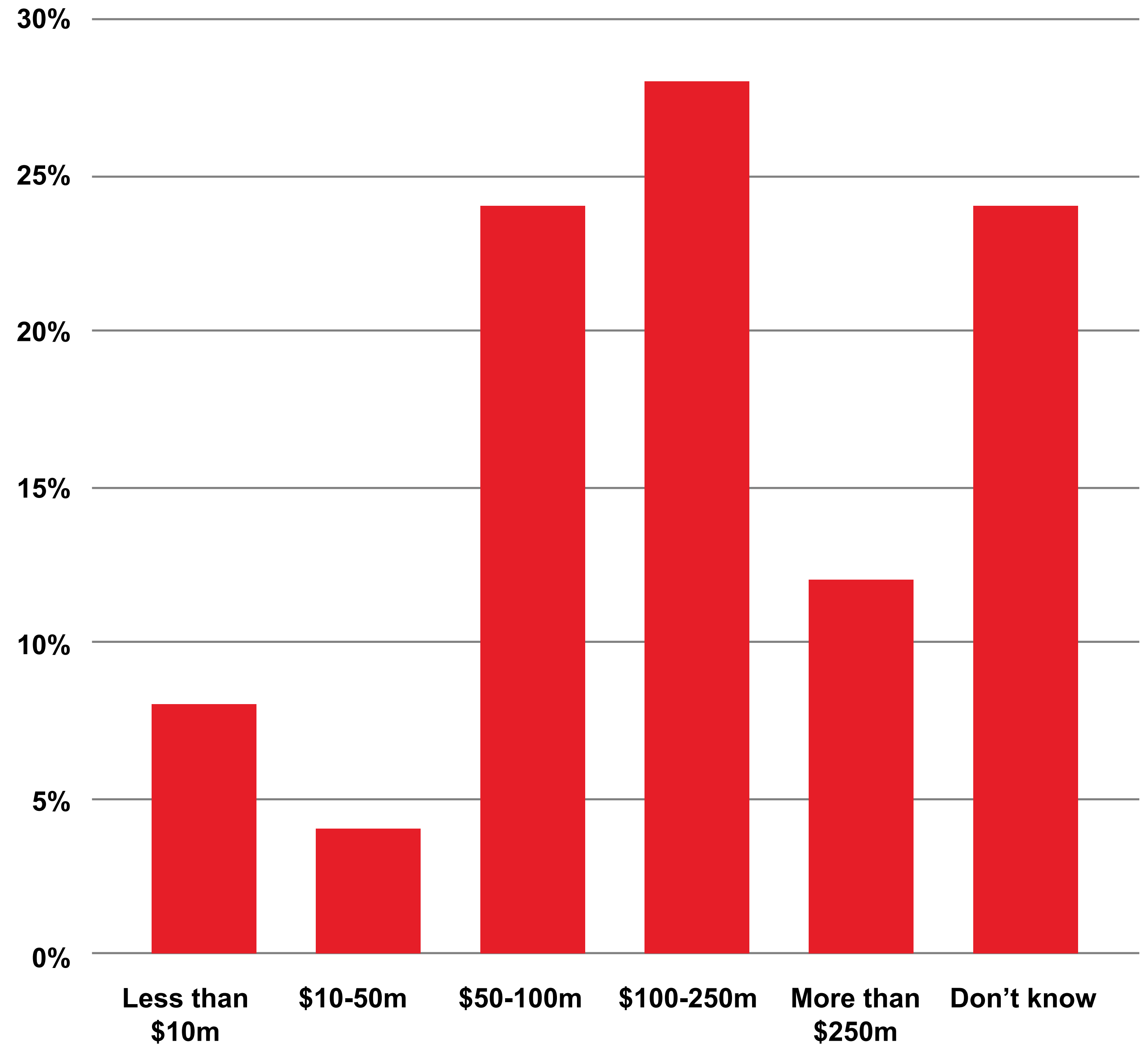


This section describes the different methods of transporting hydrogen and describes why storage is important, where the best solution will be highly dependent on local conditions. It concludes with an overview of the barriers and enablers for hydrogen transport and storage.

Investors are most bullish about Western Europe, followed by North America. One in four respondents to the survey admitted that they were unsure of how much investment their organisation would make in hydrogen T&S infrastructure by 2025. It is interesting that, of those that did have an idea, the highest proportion (28%) were expecting to invest between $100 and 250m by 2025 followed by the $50m to 100m bucket (24%). More than 10% of respondents said that they were targeting more than $250m investment in hydrogen T&S infrastructure before 2025.

The responses in the T&S category have a similar pattern to those for production infrastructure, indicating that investors are more confident about these two stages in the value chain.

Scale of expected investment by 2025 - Transport &Storage



The Role of Hydrogen Transport and Storage Infrastructure

Policy, regulations and market forces in each country will dictate how the hydrogen ecosystem emerges and matures.

The role of hydrogen transport and storage (T&S) infrastructure will evolve over time as the hydrogen economy takes hold. The path of this evolution will depend on local conditions, most notably the extent to which existing infrastructure for fossil-derived products is developed and could be shared or repurposed.

Likewise, the evolutionary process will depend on local dynamics of supply and demand, including whether it makes sense to import or export hydrogen based on local conditions.

With all else being equal and allowing for the unique conditions of each jurisdiction, it is expected that the hydrogen economy will evolve approximately as follows:

Local hydrogen markets (Hydrogen hubs/ clusters) → **Regional hydrogen markets** → **National & international networks/markets**

Localised clusters with a small number of players will increase in size and join up to form regional markets, which may become interconnected to form national networks. This is not to say that the progression from one stage to the next will be inevitable or consistent across the market. It may be that some jurisdictions are suited to having clusters of local hydrogen systems that never grow to regional scale or become inter-linked to produce a national network.

The policy, regulations and market forces in each country will dictate how the hydrogen ecosystem emerges and matures. In addition, hydrogen could be imported or exported at any of these scales, depending on the relative favourability of producing hydrogen in that location relative to others in the global market (to the extent to which it is established).

Countries without existing natural gas networks might decide to remain at the stage of regional markets with limited trade between them if establishing a nationwide network is seen as too costly or unnecessary. On the other hand, jurisdictions with existing natural gas networks will need to plan the transition carefully to determine if and how the network will transition from natural gas to hydrogen.

Local hydrogen markets

Initially as the market takes root, hydrogen production and end-use will tend to be co-located in isolated areas. Where these clusters emerge will be determined by locations having the required resources available for low carbon hydrogen production, a baseload of hydrogen demand and financial support from government to support the transition to low carbon hydrogen. At this stage, hydrogen T&S requirements can largely be provided by compressed gas storage tanks and tube trailers, with dedicated hydrogen pipelines and liquid storage and transport solutions utilised where this suits local conditions.

Regional hydrogen markets

As the number of local markets increases and expand in size, economies of scale will apply and reduce costs, creating a virtuous cycle. Thus, local nodes will eventually merge with each other to create larger regional markets. At this stage in the development of the hydrogen economy, hydrogen could begin to enter regional gas distribution networks and large-scale hydrogen storage solutions could be required depending on the local conditions and hydrogen applications.

National and international hydrogen markets

If trade between regions becomes established, it is expected that a national market will eventually develop. This could mean a need for 100% hydrogen transmission networks and a role for non-physical hydrogen storage media (e.g. liquid organic hydrogen carriers, ammonia and methanol). There will also be opportunities for international trade, as some regions expect a domestic low carbon hydrogen production shortfall compared with demand, which will require importing from regions where conditions are more conducive for hydrogen production.

> "We've already mentioned the chicken and the egg, so you know it is a hydrogen conversation…don't forget the nest. You can think of the infrastructure that we have as the nest…you've got to get it there somehow and you've got to store it somehow."
>
> Peter Durante, Head of Technology and Innovation, Macquarie Asset Management

Transport and storage solutions for various market sizes

The T&S infrastructure for hydrogen will be selected to suit the scale of the application. The table provides an indicative summary of the technologies that would be suited to each stage of market development as well as for bulk import and export applications.

The very low density of hydrogen makes it challenging to store – whether it be for static applications or transport – because each Joule of energy takes up more space than traditional fossil fuels. For small scale applications (e.g. localised markets), storage of hydrogen as a compressed gas makes the most sense. This is because the processing required to make it more dense – liquefication, storage in liquid organic hydrogen carriers (LOHC) or metal hydrides, conversion to other molecules (e.g. ammonia and methanol) – all come with an energy penalty that increases the cost of hydrogen at the point of use. For the same reason, moving hydrogen as a gas within pipes is generally the most cost-effective approach, where this is practical. Piping systems can also be operated at higher pressure to double as storage – a practice known as line-packing. However, when pipes are not practical (e.g. export across oceans or delivery to dispersed consumers), then processing for storage and transport by various other modes must be considered. The optimal solution depends on the local conditions and existing transport infrastructure.

Plant and equipment for storage in tanks as a compressed gas or liquid is commercially mature, but cryogenic liquefaction plants are not common because there has traditionally not been high demand for liquid hydrogen outside of space exploration. Conversion to other molecules such as ammonia and methanol are commercially mature technologies applied in the chemical sector. While LOHCs and metal hydride storage is yet to achieve maturity at commercial scale, the technology is well understood and is expected to become established as the demand for hydrogen grows.

	Storage Type				Storage Type / Transport mode	Transport mode					
	Tanks	Tanks	Tanks	Geological	Pipeline	Tube trailer truck	Tanker truck	Truck	Rail	Small vessel/ barge	Large ship
State for transport/ storage	Compressed gas	Liquid hydrogen	LOHC*, other molecules**	Compressed gas	Compressed gas	Compressed gas	Liquid hydrogen, LOHC*, other molecules**	Metal hydride	All	All	All
Import and export	Low	Medium	High	Depends on application/local conditions	Low	Low	Low	Low	Depends on application/local conditions	Depends on application/local conditions	High
Local markets	High	Medium	Low	Low	Medium	High	Medium	Low	Low	Depends on application/local conditions	Low
Regional markets	Medium	Medium	Low	Depends on application/local conditions	Medium	Medium	Medium	Low	Depends on application/local conditions	Depends on application/local conditions	Low
National and international markets	Low	Low	Medium	Depends on application/local conditions	High	Medium	Medium	Low	Depends on application/local conditions	Depends on application/local conditions	Medium

Legend: Relative applicability at each scale:

- Low
- Medium
- High
- Depends on application/local conditions

*LOHC: Liquid organic hydrogen carrier
** E.g. Ammonia, methanol

Hydrogen piping networks – an important role to play locally, regionally & nationally?

Transporting low carbon hydrogen through pipelines is an efficient means of delivering large quantities of hydrogen, so piping networks have an important role to play at each stage of market development.

Network effects dictate that the marginal cost of using the system decreases as more market participants (producers and consumers) connect to a hydrogen piping system. As well as reducing the costs of T&S, it also fosters competition, further reducing the price of hydrogen. Therefore, piping networks, whether at the local, regional or national scale, could have an important part to play in the hydrogen market, especially in jurisdictions with existing gas networks.

Network and storage for local markets

There are many 100% hydrogen pipelines that are currently operational globally, which supply large-scale industrial hydrogen users such as oil refineries and chemical production facilities. These typically connect a single producer to one or two consumers that have few (if any) alternative supplies. A key step would be to establish networks with multiple local producers and off takers to foster competition and reduce shared costs.

Network and storage for regional markets

At a regional level, existing gas distribution networks may begin to carry a proportion of hydrogen to commercial and domestic users. The technical and safety implications of this transition are currently being explored, as regulators and network operators examine the impact that hydrogen will have on distribution network assets, including pipework and compressors. Further research and development will also be required to understand the technical and safety implications of transporting high pressure hydrogen in steel pipework, particularly the potential for hydrogen embrittlement of steel.

A regional hydrogen market will also have different storage requirements. This will be dependent on the size, location and the end-uses of hydrogen. Whilst above ground storage will likely still form the majority of the storage, it may be cost effective to utilise geological storage solutions for large-scale applications. This is especially where readily available salt caverns exist, and where hydrogen substitutes natural gas in distribution networks to provide space heating needs for domestic and commercial customers. Space heating generally sees large inter-seasonal fluctuations in demand, possibly requiring large-scale storage to meet winter excess demand.

Network and storage for national and international markets

If national and international hydrogen markets develop, nationwide and continental hydrogen transmission networks may be required to facilitate large flows of low carbon hydrogen from regions with excess production to those that have a deficit.

Given the scale at which national and international hydrogen markets will operate, there will be an increased need for large-scale storage solutions, with compressed gas geological storage sites favourable where geography allows. Non-physical storage solutions (e.g. LOHC, metal hydrides and other molecules) will also have an increased role to play at this larger scale because they become more practical than compressed gas storage in tanks due to space requirements in above-ground applications.

Hydrogen Blending

Hydrogen blending is a good transitionary option in jurisdictions that have existing gas networks, as it will allow for partial decarbonisation of the existing natural gas network whilst allowing for hydrogen production to scaled up.

Blending could occur relatively early in the development of the low carbon hydrogen market, even before regional markets are fully developed. Studies around the world are examining the feasibility of blending hydrogen with natural gas up to 20% by volume, which is about the limit for domestic boilers.

Regulators are investigating the impact this will have on the safe operation and maintenance of distribution and transmission infrastructure as well as the compatibility with end-user appliances. The difficulty with serving a range of consumer segments through a single network is that the range of appliances and equipment that use the gas (including industrial and commercial users) might have different limits for hydrogen blending.

The safe limit for hydrogen blending is important because beyond this point, incremental increases are not technically feasible and a step change to 100% hydrogen is required in the network. This change means that a gradual transition over time is not an option and governments will need to provide a clear strategy as to if, how and when they will switch from a blend of natural gas and hydrogen to 100% hydrogen. This will be no trivial task considering the sheer number of installed end-user equipment that would need to be modified or replaced, especially if space heating is involved. Such a fundamental shift will require years for planning and roll-out.

> "There is certainly lots of activity in the midstream space following the clear intent from the TSOs to either blend hydrogen or build H2 networks"
>
> Marguerite

Barriers and enablers for investment in hydrogen transport and storage infrastructure

Policy makers and regulators must design appropriate funding mechanisms to support the transition towards hydrogen.

The barriers and enablers for investment in hydrogen transport and storage infrastructure will differ by jurisdiction depending on the maturity of the market and whether existing piping networks are available.

In the absence of piping systems, the market for transport of hydrogen by road, rail or water will be relatively competitive because existing service providers can easily expand their capability to cater for hydrogen distribution. Governments may seek to intervene in the early stages to encourage growth to a competitive scale, but this would be relatively light touch compared to the level of policy coordination and regulation that is required for piping systems.

Just like gas networks and electricity grids, a hydrogen network will tend to be a natural monopoly where it is most economically efficient to have a single owner that is subject to regulation rather than parallel competing systems. A supportive regulatory regime and government financial support for research, development and demonstration projects will be essential to support the technical and safety case for hydrogen networks and provide a sustainable business model for private sector investment.

Transmission and distribution assets

The adaptation and transition of existing network infrastructure to be compatible with 100% hydrogen will require significant levels of investment. It is important that policy makers and regulators design appropriate funding mechanisms to support the transition towards hydrogen. In the early stages this will involve research, feasibility studies and demonstration projects to fully understand the impact that hydrogen will have on existing network infrastructure.

Worldwide, gas and electricity networks have had to evolve in response to growing demand and changing production technologies e.g. increasing penetration of variable renewable energy generation. This has led to policy makers and regulators introducing new regulatory models to introduce competition into network development and growth as well as respond to changing network characteristics. Examples include auctions for concessional ownership of transmission assets subject to regulation as well as various incarnations of a regulated asset base (RAB) model. There are multiple case studies of various approaches that have emerged within the electricity and gas sectors in recent years as markets have liberalised. The best approach will depend on the stage of market maturity and the unique characteristics each jurisdiction.

Blending hydrogen with natural gas presents a different challenge to establishing 100% hydrogen networks. Regulators will need to ensure that any modifications which need to be made to network infrastructure are factored into regulatory mechanisms to facilitate private sector involvement in the sector.

Engagement with end-users will be vital to foster adoption of appliances and infrastructure (including metering) that enable 100% hydrogen to be used instead of natural gas.

Storage assets

If a national hydrogen network is considered appropriate for a jurisdiction, then government funding will be essential to drive research and development for viable large-scale storage solutions to accommodate seasonal differences in demand. In addition, lessons from the natural gas sector suggest that ongoing support mechanisms might be required to attract investment and provide a business case in the long term. The value of hydrogen storage in a future national network is likely to be driven by similar price signals to the current natural gas market, including:

- The spread between summer / winter hub price spreads which determines the value of seasonal flexibility, and
- The spot price volatility which determines the value of short-term gas delivery flexibility.

These signals tend to be highly cyclical, and declining spreads in Europe in the 2010s have made it difficult for storage owners to cover their costs. In some jurisdictions, there has been a decline in storage capacity over the past decade which reflects this challenging market.

Therefore, policy support through appropriate commercial models might be required to sustain the hydrogen storage market at a national scale in the future to ensure system resilience and meet inter-seasonal fluctuations in hydrogen demand. These considerations should be investigated in detail before governments make strategic decisions about whether to pursue a national hydrogen network or not.

Summary of barriers and enablers to hydrogen infrastructure investment across the value chain

This section pulls together the findings of the previous sections to present the barriers and enablers across the full value chain for low carbon hydrogen. Some of these are cross-cutting, but others are particular to production, T&S or end-use.

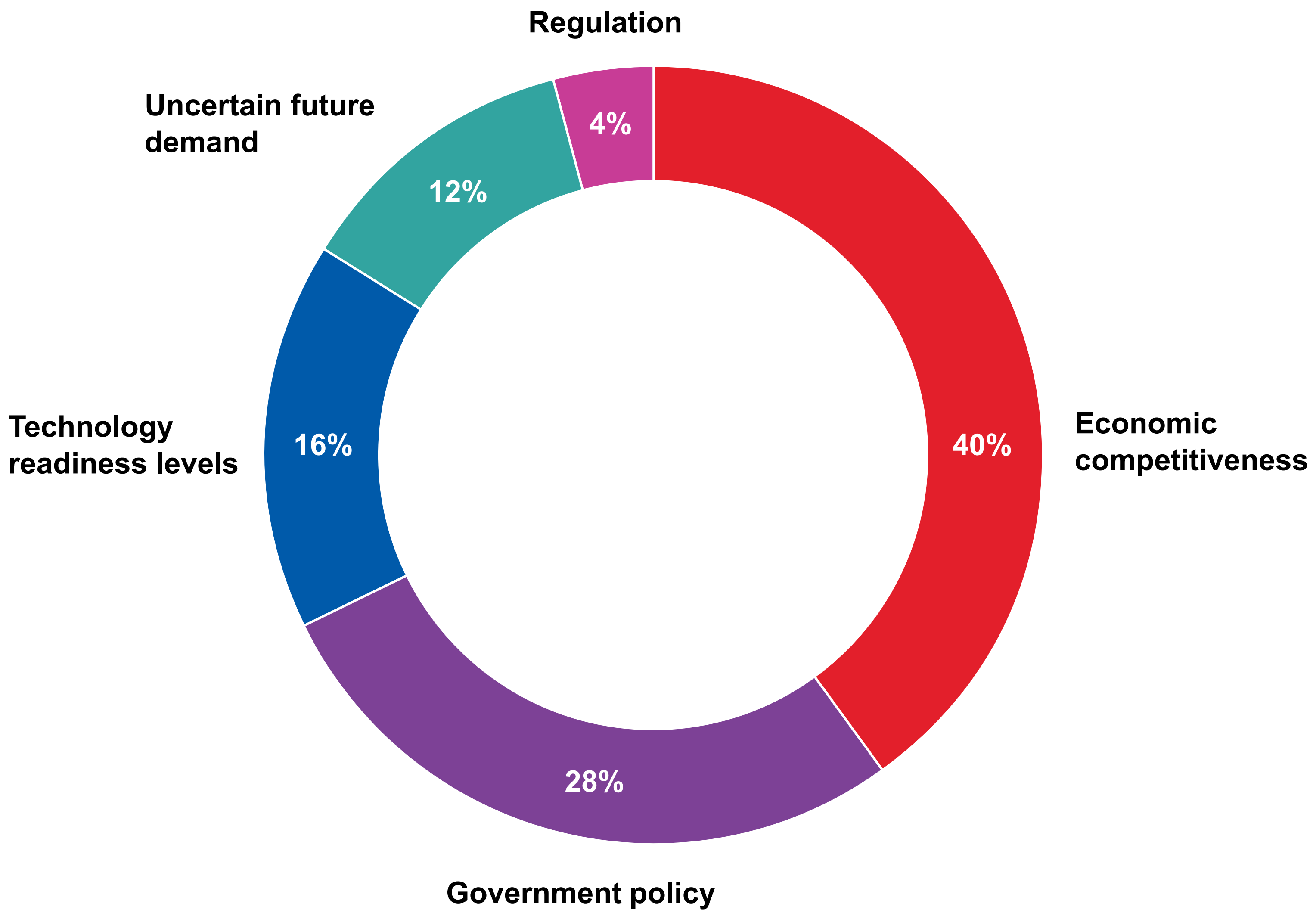
Before diving into the analysis, it is useful to see what investors think about these topics.

"There's that constant challenge for a regulator of thinking with a long-term perspective; appreciating that new technologies will cost more to begin with. How do you put in those stage gates to check whether the cost coming down in line with expectations that we would understand through learning curve effects and/or scale effects? And if they're not, then you revisit and ask: 'Why are we doing this? Is there a better way to do it?' There are some clear parallels to previous experience supporting renewables and electric vehicles."

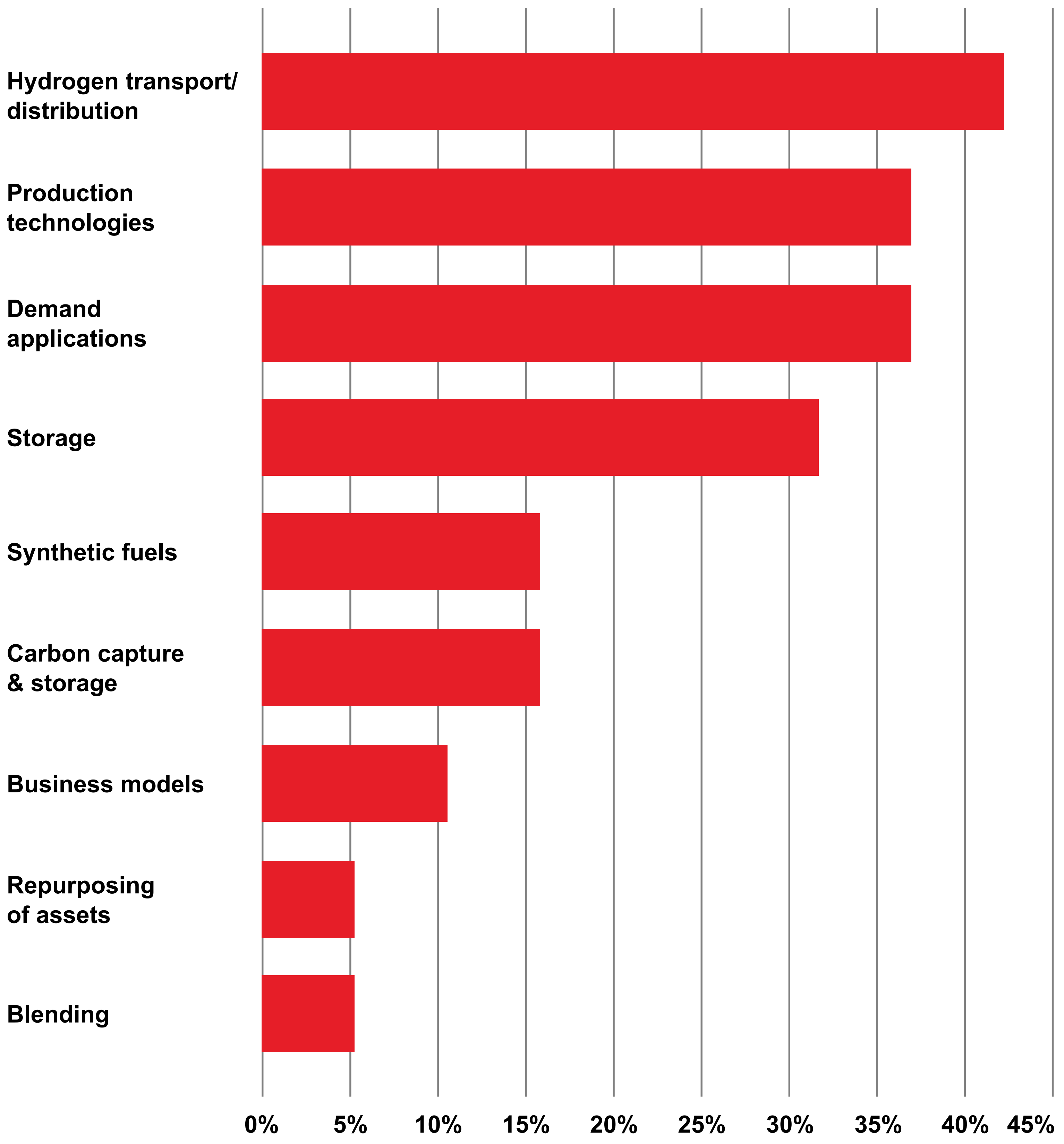
Macquarie

Investor opinions about main barriers to investment in hydrogen infrastructure and enablers to unlock investment

What is the biggest barrier to investment in hydrogen infrastructure?



Top areas requiring further R&D (proportion of respondents identifying each area)



Summary analysis of barriers and enablers

Navigating risk is part of the day job for investors, but there are still significant uncertainties about the role hydrogen could play as the global economy seeks to decarbonise its activity.

Public sector intervention is required to create an enabling environment for investment and to reduce the risks that face investors in the early stages of the market.

The primary barrier to adoption of low carbon hydrogen is its high cost relative to the carbon-intensive fuels that have underpinned global economic progress since the Industrial Revolution. To overcome this barrier, each jurisdiction needs to find the best combination of measures to stimulate adoption of hydrogen while discouraging the use of polluting fossil fuels.

In broad terms, for the hydrogen market to emerge in an economically efficient way, the supply push should be in concert with the demand pull at each stage of its development. Even in established sectors it is a challenge setting balanced and effective policy and regulation, so getting this right for hydrogen will be especially difficult considering the many uncertainties that the market faces.

A careful balance needs to be struck between creating an enabling environment for market forces to drive down prices, while not over-burdening taxpayers or ratepayers through undue largesse. This will not be an easy task but there are valuable lessons that are still fresh in the memory from the scale-up of renewable energy technologies, batteries and electric vehicles in recent years. The worst mistake would be to give up before even trying.

However, there are other measures that cut across the value chain that can drive the growth of the hydrogen sector. These include:

– Funding for research and development of hydrogen systems and technologies. Public sector intervention can taper off as the market matures and competitive forces incentivise institutions and companies to self-fund innovation

– Internalising the cost of greenhouse gas emissions throughout the supply chain so that the negative effectives of carbon-intensive economic activity are better accounted for

– Providing a transparent and robust certification system to ensure that emissions for low carbon hydrogen are assessed over the full lifecycle according to clearly defined standards that are monitored, certified and enforced

– Progressively reducing legacy subsidies for production and use of carbon-intensive technologies.

The most effective measures differ depending on the stage in the value chain and the specific application. Various measures have been discussed in the previous sections of this report and the key messages are summarised in the following pages.

> "There's a lot of capital that is ready to be put to work in investing in the development of these projects and if there is a clear framework for compensation the capital is there."
>
> North American Pension Fund

Barriers and proposed enablers for hydrogen production

The key barriers to investment and economic principles for public sector intervention in the production side of the value chain are listed in the table together with proposed enablers as well as case studies where this has been successful in other sectors.

54%

respondents said barriers to production is hindering investment.

"What matters is after you reach the stated production capacity to be tendered, you stop the subsidy so that people know that there is a window and they have to sharpen their pencil to get there and provide the best production cost they could deliver. But the subsidised volume must be finite."

European Fund Manager

Barrier/principle	Proposed enablers	Example case study
Financial uncertainty The private sector needs clear financial incentives to provide price certainty to underpin future revenue streams and have the confidence to invest in early-stage projects.	The most cited measure is a type of contract for difference (CfD) that compensates the producer for the price between hydrogen and the fuel it is replacing.	UK CfD for renewable energy technologies.
Long-term risk concerns Minimise the risk of investing in early-stage technologies that could become uncompetitive in the future as innovation increases.	Commit to long term contracts that offer revenue certainty well into the future.	
Public funds / customer costs Subsidies are often funded through tariffs or taxes - these must be progressive and avoid over-burdening public funds or customer prices.	Reverse auctions with a defined budget and scope (e.g. eligible production technologies) allow these to be tendered competitively.	Australian Capital Territory's reverse auctions for renewable energy.
Costs of failed technology The private sector should not be expected to bear the burden of technology failure risk in the early stages.	Where technology allows, start small with demonstration projects and scale-up quickly once proven. Public-private partnerships for first-of-a-kind projects with appropriate risk-sharing.	Development of small modular reactors in the nuclear sector.
Demonstrating demand Investors need to have confidence that there will be a demand for the hydrogen they produce.	Demand-side mandates for end-use sectors. Take-or-pay offtake agreements. See measures in next subsection.	Take-or-pay agreements for independent power producers.

Barriers and proposed enablers for hydrogen adoption in end-use applications

A fundamental challenge for increasing demand for low carbon hydrogen is that the potential applications span across a range of sectors, which are typically governed by different government departments and regulated differently.

The adoption of hydrogen in these disparate sectors will require unprecedented coordination in terms of strategy, policy and regulation to reduce risks of unintended consequences. For example, a well-intended but overly generous subsidy to decarbonise passenger vehicles could divert hydrogen away from applications where it might reduce emissions in a more efficient manner (e.g. heavy industry).

The key barriers to investment in hydrogen end-use infrastructure and economic principles for public sector intervention are summarised in the table, again with suggested enablers and case studies.

> "When providing support, governments must decide what sort of things they want to back [in the early stages of the market] otherwise the impact of that money won't be very meaningful."
>
> European Fund Manager

Barrier/principle	Proposed enablers	Example case study
Competition In the early stages of hydrogen market development (when costs are comparatively high) prioritise applications where the alternatives for decarbonisation are limited.	Governments should target demand-side interventions starting with applications that have high marginal costs of abatement (e.g. processes where unabated fossil-derived hydrogen is currently used).	Norway's range of incentives for purchase of electric vehicles.
Lower-cost high carbon alternatives These prevent hydrogen solutions from gaining market share.	Demand side mandates, public procurement quotas.	Brazil's mandates for blending ethanol with gasoline.
	Outright bans on polluting technologies with sufficient notice for the market to adjust.	UK Government's announced bans on coal-fired power plants by 2024 and gasoline & diesel vehicles by 2030.
	Tax credits and exemptions.	United States' investment tax credit for renewable electricity technologies.
Long-term supply concerns Investors need to have confidence that there will be a supply of low carbon hydrogen for them to consume into the future.	Long term offtake agreements with producers. Clear revenue support mechanisms for producers.	Power purchase agreements for independent power producers.

Barriers and proposed enablers for transport and storage of hydrogen

The options available for transport and storage of hydrogen are largely dependent on the existing gas transmission, distribution, and storage infrastructure as well as the stage of hydrogen market development.

In jurisdictions where hydrogen will be transported primarily by road, rail, or water; it is anticipated that a relatively competitive market between service providers will emerge naturally as supply and demand grows.

Governments may seek to intervene in the early stages to encourage growth, but the policy and regulatory considerations would be relatively minor compared to jurisdictions where national hydrogen networks are being considered.

For jurisdictions that have established gas networks, the following enablers will be required to increase the proportion of hydrogen transported through the network to the technical limit of about 20% (by volume) to achieve an incremental reduction in emissions.

Barrier/principle	Proposed enablers
Future uncertainties Industry stakeholders (gas network operators, end-users, hydrogen producers, regulators) need to see a clear path to increased proportions of hydrogen in the network so they can plan accordingly.	Governments should develop a clear plan with time-bound milestones for key policy decisions, underpinned by the necessary studies about safety and value-for-money.
What regulations ahead? Uncertainty about regulatory models for different types of hydrogen or blended networks could stifle investment.	Governments and regulators should provide clarity about the proposed approach to regulation (e.g. details of RAB models) for different types and scale of networks that might be required.
Resource concerns Gas network operators are accustomed to mature natural gas markets and do not have the resources to manage the uncertainties of an emerging hydrogen market.	Implement updated network regulatory and funding models which support network operators with the hydrogen transition.
	In the early stages, provide clear direction about areas that are likely to be early adopters of hydrogen so that planners can forecast changes in supply and demand.
A reluctant market? End-user reluctance to adopt hydrogen technologies	Funding for research and development, to allow for the technical and safety case for hydrogen networks to be established and allow relevant regulations to be updated.
	Well-funded, comprehensive public engagement to socialise the findings of the technical and safety studies.
	Well publicised pilot and demonstration projects to show that hydrogen can be used as safely and conveniently as the high-carbon alternatives it is replacing.

Measures for 100% hydrogen networks

Where large hydrogen piping networks are an option for the future (either new purpose-built infrastructure or repurposed natural gas infrastructure), the following enablers will be required.

> “Hydrogen is an option to mitigate the risk of stranded assets for pipelines in Europe.”
>
> Pension Fund

Barrier/principle	Proposed enablers	Example case study
Path to network expansion Industry stakeholders (gas network operators, end-users, hydrogen producers, regulators) need certainty about the key steps on the path to deciding whether to establish a large-scale hydrogen network.	Governments should develop a clear plan with time-bound milestones for key policy decisions. This should strike a balance between allowing enough time to gather evidence about the potential impact on all stakeholders and avoiding undue delays affecting investment decisions in the enabling infrastructure.	UK in the 1970s pursuing a policy of a national gas network
Regulation clarity If the government decides to pursue large scale hydrogen networks, stakeholders will need clarity about how the infrastructure will be regulated.	Governments and regulators should consult with industry stakeholders about the best approach to regulating hydrogen piping and storage assets as well as possible funding mechanisms.	Draw on lessons from liberalisation of gas and electricity sectors across the world.
Support mechanisms If the government decides to pursue large scale hydrogen networks, investors will need details about the proposed support mechanisms to correct for market failures.		

Socio-economic and policy considerations

The development of the hydrogen economy must be carefully planned and implemented with impact on communities, livelihoods and the environment in mind.

As with any suite of policy measures, there is a need to consider the range of economic, social and environmental implications of making any interventions. The fossil fuel sector is a vital part of all economies because we have become reliant on it to drive economic growth, albeit in a polluting way.

Hence, in addition to the technical and market uncertainties discussed above, there are significant socio-economic risks associated with transitioning away from fossil fuels in favour of low carbon alternatives, including hydrogen. Workers' livelihoods and the wellbeing of entire communities are at stake and need to be safeguarded. These aspects as well as environmental impacts need to be carefully considered at every stage to ensure that the transition is equitable as well as profitable.

In the spirit of safeguarding the environment, governments and regulators should beware of creating perverse incentives that end up having a net negative impact on the environment. For example, one potential pitfall is to create incentives for the production of green hydrogen that divert renewable sources from supplying to the electricity grid and ultimately undermines the decarbonisation of the electricity system. To guard against this threat, the concept of renewable additionality is important, as discussed earlier in this report.

Another threat to environmental and social wellbeing is harmful land use change, where the building of low carbon infrastructure (e.g. solar farms) displaces other activities such as agriculture, which ultimately moves to other land at the expense of natural habitats and biodiversity. This pitfall can be avoided through proper regulation of environmental and social impacts in the development phase of projects.

The bottom line - Balanced public sector involvement is vital for the hydrogen economy to take off

Investors are poised – they now need governments and policy makers to offer the support and reassurance they require.

Investors broadly agree that low carbon hydrogen will play an important part in the effort to decarbonise the global economy. How much of a role it will play by 2050 is a matter for debate, but significant growth is required immediately from the current low base. This will not happen without public sector support because the economics of the hydrogen economy do not currently justify large investments when compared with carbon intensive alternatives.

A clear time-bound plan

The capital is ready and waiting to be deployed, but governments need to articulate a clear time-bound plan to provide the certainty that the private sector needs to make investment decisions. Strategies and targets for hydrogen deployment are a good start but they do not go far enough – more tangible actions are required to create a credible market for hydrogen products and infrastructure. This report provides a menu of interventions that can be selected to suit the unique characteristics of each jurisdiction.

Provide price certainty and foster demand

To encourage growth in the supply of hydrogen in the next few years, investors need to see long term support for revenue through price certainty. On the other hand, the supply push needs to be matched by the demand pull so that producers have confidence that there will be a market for their hydrogen. This calls for interventions in end-use sector to stimulate demand and, where applicable, subsidies for producers – with the knowledge that any subsidy would need to be tapered off over time as the market develops.

Focus on applications with low risks of future regret

In the early stages of the market, end-use interventions should focus on the applications where there are low risks of future regret and where the marginal costs of carbon abatement are high. Industrial processes that already consume fossil-derived hydrogen are a good place to start (e.g. refineries, chemical plants) as well as thermal processes requiring high temperature heat (e.g. manufacture of steel and cement). Sustainable aviation fuels could also be considered along with low carbon maritime fuels.

Evaluate production pathways on their merits

All low carbon production methods should be on the table, provided the emission reductions are assessed over the full lifecycle according to clearly defined standards that are monitored, certified and enforced. Hydrogen production from fossil fuels with carbon capture and storage offers an opportunity to scale up supply quickly while the supply chains for green hydrogen expand and capital costs fall through economies of scale and innovation.

Prioritise research and development in demand applications

On the subject of innovation, increased public sector funding for research and development is required across all stages of the supply chain to foster competition and increase efficiencies. Innovation in hydrogen end-use applications should be prioritised so that more hydrogen-consuming technologies find their way to market. Production will follow naturally, provided the necessary price support is in place.

Sort out regulations to enable blending into gas networks

For jurisdictions with existing gas networks, hydrogen blending should be pursued as a matter of urgency with regulations and safety cases developed to facilitate this. Governments also need to articulate a clear path for gathering the evidence that is required to decide whether to convert to 100% hydrogen supply in the future and how that will be achieved.

The raw materials are available – investors have the capital and the manufacturers have the technologies – they are just waiting for the public sector to catalyse the reaction. The time for decisive action has arrived.

Glossary

$	United States dollars
AU$	Australian dollars
CCS	Carbon capture and storage
CCUS	Carbon capture, use and storage
CfD	Contract for difference
COP26	Conference of the Parties 26
EU	European Union
GHG	Greenhouse gas emissions
GIIA	Global Infrastructure Investor Association
GW	Gigawatts
HHV	Higher heating value
Kg	Kilogram
LOHC	Liquid organic hydrogen carrier
PEM	Proton exchange membrane
R&D	Research and development
RAB	Regulated asset base
SMR	Steam methane reforming
T&S	Transport and storage
TSO	Transmission system operator
TWh	Terrawatt-hours
UK	United Kingdom

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